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Incremental Filling Technique and Composite Material—Part II: Shrinkage and Shrinkage Stresses

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Clinical Relevance

Using low-shrink composites applied in medium increment sizes of approximately 2 mm provided the best balance compared to bulk or 1-mm increment placements.

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DOI: 10.2341/12-442-L

SUMMARY

Objectives: **Finite element analysis (FEA) was used to study polymerization shrinkage stress in molars restored with composites and to correlate those stresses with experimentally measured tooth deformation.**

Methods: **Three composites (Filtek LS, Aelite LS Posterior, Filtek Supreme) and three filling techniques (bulk, 2.0-mm increments, and 1.0-mm increments) for restoring a molar were simulated in a two-dimensional FEA. Polymerization shrinkage was modeled using post-gel shrinkage, which was measured using the strain gauge technique (n=10). Cuspal tooth deformation, measured at the buccal and lingual surfaces with strain gauges in a laboratory study, was used to validate the analysis. Residual shrinkage stresses were expressed in modified von Mises equivalent stresses. Linear Pearson correlations were determined between the laboratory and FEA results.**

Results: **Post-gel shrinkage values (in volume %) were: Filtek LS (0.11 $\pm$ 0.03) $<$ Aelite LS Posterior (0.51 $\pm$ 0.02) $<$ Filtek Supreme (0.62 $\pm$ 0.09). The 1.0-mm increment filling caused substantially higher stresses and strains in the**

cervical enamel region. Significant correlations were found between: elastic modulus and FEA strain, elastic modulus and FEA stress, post-gel shrinkage and FEA strain, post-gel shrinkage and FEA stress, FEA strain and cuspal deformation by strain gauge, and FEA stress and cuspal deformation by strain gauge ($p<0.05$).

Conclusions: **Increasing the number of increments and high post-gel shrinkage and/or elastic modulus values caused higher stresses in the remaining tooth structure and tooth/restoration interface. Cuspal deformation measured with the strain gauge method validated the finite element analyses.**

INTRODUCTION

Composite resins are widely used in dentistry to restore teeth with structural loss due to their esthetics and physical properties. However, these restoratives have polymerization shrinkage as an inherent problem that may cause residual stresses in the tooth, even when not in function.[1,2] Clinical signs that have been associated with polymerization shrinkage stress include inadequate adaptation at tooth/restoration interface, micro-cracking, postoperative sensitivity, microleakage, and secondary caries.[3,4] These issues are often responsible for replacement of composite restorations in posterior teeth.[5,6] Changes in material formulations and filling techniques, aimed at reducing volumetric contraction and shrinkage stress, have been the primary approaches for reducing the development of residual stresses.[7,8]

Restorative composite formulations have been continuously improved by modifying filler content[9] and monomer types.[10] Silorane-based composites were developed to minimize the polymerization contraction. These monomers are derived from a chemical combination between the components of siloxanes and oxiranes.[11] The polymerization reaction occurs by photo cationic ring opening, and results in a lower polymerization shrinkage compared with resins that are based on methacrylates.[12] Another important physical property that influences the stress development is the elastic modulus, which is also associated with the composition of a material. Elastic modulus has been shown to increase with filler content.[13,14] Since an increase in elastic modulus will increase the stress under the same strain conditions, an increase in elastic modulus tends to increase residual shrinkage stresses. Manufacturers may be tempted to produce new low-shrink composites by reducing the elastic modulus. However, if the elastic modulus is low, the restorative material may not sufficiently recover the structural integrity of the original tooth to support masticatory loads.[14] Composite resins with high elastic modulus produce more rigid restorations, which increase the effect of polymerization contraction on residual shrinkage stresses.[15]

Filling techniques also influence stress distributions. The potential of incremental composite placement technique to reduce the shrinkage deformation and stress at the adhesive interface is controversial.[16-18] An incremental technique could increase shrinkage stresses due to incremental cuspal deformation by each polymerized increment. The incremental cuspal deformation also leads to a reduction in the volume of the cavity, reducing the amount of composite that is placed in subsequent increments.[18]

A previous study, which will be referred to as Part I, examined the effect of composite resin type and filling technique on cuspal deflection, microtensile bond strength, and mechanical properties of the composite resins in class II restorations.[19] It was found that restorative techniques that cured restorations in 8 (2.0-mm) or 16 (1.0-mm) increments instead of bulk increased cuspal strains. However, the influence of these factors on the shrinkage stress inside the composite restoration, tooth structure, or along the adhesive interface could not be determined by the laboratory tests.

The purpose of this study was to evaluate further the outcomes of the experimental results by correlating cuspal deformations for different composite materials and filling techniques with residual shrinkage stresses using finite element analysis (FEA). The post-gel shrinkage values required for the stress analyses were determined experimentally using the strain gauge method, while the elastic modulus values obtained in Part I are used in the shrinkage stress calculations.

MATERIALS AND METHODS

Post-gel Shrinkage Measurements

Composite post-gel linear shrinkage was determined using the strain gauge method.[20] The materials used in this study were two low shrink composite resins, Filtek LS (LS) and Aelite LS Posterior (AE), and one conventional composite resin, Filtek Supreme (SU). Their composition and manufacturer information are listed in Table 1. The composite resin was shaped into a hemisphere and placed on top of a biaxial strain gauge (CEA-06-032WT-120, Measurements

Table 1: *Dental Composites Tested in the Study (Information Provided by the Respective Manufacturers)*

Composite Resins	Wt%	Vol%	Filler Type	Matrix	Manufacturer
Filtek LS	76	55	Quartz and yttrium fluoride (0.1-2.0 μm)	TEGDMA and ECHCPMS	3M ESPE, St Paul, MN, USA
Aelite LS Posterior	84	74	1.1 μm	Bis-GMA and UDMA	BISCO, Schaumburg, IL, USA
Filtek Supreme	82	60	Silica nanofillers (75 nm) zirconia nanofillers (5-10 nm) and agglomerated zirconia/silica nanoclusters (600-1400 nm)	Bis-GMA, Bis-EMA, UDMA, TEGDMA	3M ESPE, St Paul, MN, USA

Abbreviations: Bis-EMA, bisphenol-A hexaethoxylated dimethacrylate; Bis-GMA, bisphenol-A glycol dimethacrylate; ECHCPMS, 3,4-epoxycyclohexylcyclopolymethylsiloxane; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

Group, Raleigh, NC, USA) that measured shrinkage strains in two perpendicular directions. The perpendicular strains were averaged since the material properties were homogeneous and isotropic on a macro scale. The composite was light-cured using a quartz-tungsten-halogen unit (Demetron, Kerr, Orange, CA, USA) with the light tip placed at 1-mm distance from the surface of the composite. The radiant exposure was set at 24 J/cm^2 (600 mW/cm^2 $\times$ 40 seconds). A strain conditioner (ADS0500IP, Lynx Tecnologia Eletrônica, São Paulo, SP, Brazil) converted electrical resistance changes in the strain gauge to voltage changes through a quarter-bridge circuit with an internal reference resistance. Microstrain resulting from polymerization shrinkage was monitored for 10 minutes, starting from the beginning of photoactivation. Ten specimens were tested for each composite. The post-gel shrinkage value at 10 minutes was used in the finite element analysis.

The mean shrinkage strain, which is the linear shrinkage, of the samples (n=10) was converted to percentage and multiplied by three to obtain the volumetric shrinkage. One-way analysis of variance (ANOVA) followed by Tukey honestly significant difference (HSD) post hoc tests (p=0.05) were used for the statistical analysis.

Residual Stress Calculation: Finite Element Analysis

To calculate corresponding residual stress in the tooth, a two-dimensional (2D) finite element simulation was carried out for a mesial-occlusal-distal restoration with the cavity floor in dentin. The geometric model was based on a digitized buccolingual cross section of a third molar with similar dimensions as the teeth selected in laboratory tests of Part I of this study. Coordinates were obtained using ImageJ software (public domain, Java-based image processing and analysis software developed at The National Institutes of Health, Bethesda, MD, USA). Only the cervical portion of the root was simulated since the rest of the root did not affect the coronal stress distribution.[14] A simplified boundary condition was assumed at the cut-plane of the root (fixed zero-displacements in both horizontal and vertical directions). The elastic modulus of enamel was 84 GPa and Poisson's ratio 0.30; the dentin elastic modulus was 18 GPa and the Poisson's ratio 0.23.[21] The elastic modulus values of the three composites filled by the three techniques at five restoration depths were obtained in Part I of this study. They ranged from 5-11 GPa, 5-24 GPa, and 6-15 GPa for Filtek LS, Aelite LS Posterior, and Filtek Supreme, respectively. The Poisson's ratio was chosen to be the same for all composites at 0.24.[21]

The finite element analysis was performed using MSC.Mentat (preprocessor and postprocessor) and MSC.Marc (solver) software (MSC Software Corporation, Santa Ana, CA, USA). The total number of FEA models was nine for the three different filling techniques (bulk filling, 2.0-mm increments and 1.0-mm increments) and the three composites (Filtek LS, Aelite LS Posterior, and Filtek Supreme). A plane strain condition was assumed for the tooth cross sections. Due to this 2D strain condition and consequently 2D finite element model, no distinction was made between the mesial and distal increments. The 2.0-mm and 1.0-mm increment techniques of the experimental study (Part I) were therefore simulated in 4-mm and 8-mm increments, respectively. Polymerization shrinkage was simulated by thermal analogy. Temperature was reduced by 1°C, while the linear shrinkage value (post-gel shrinkage) was entered as the coefficient of linear thermal expansion.

Modified von Mises equivalent stress was used to express the stress conditions, using compressive-tensile strength ratios of 37.3, 3.0, and 6.25 for the enamel, dentin, and composite, respectively.[22] Stress values were recorded in the integration points of each element and in nodes along material interfaces at either aspect (tooth and restoration). Linear

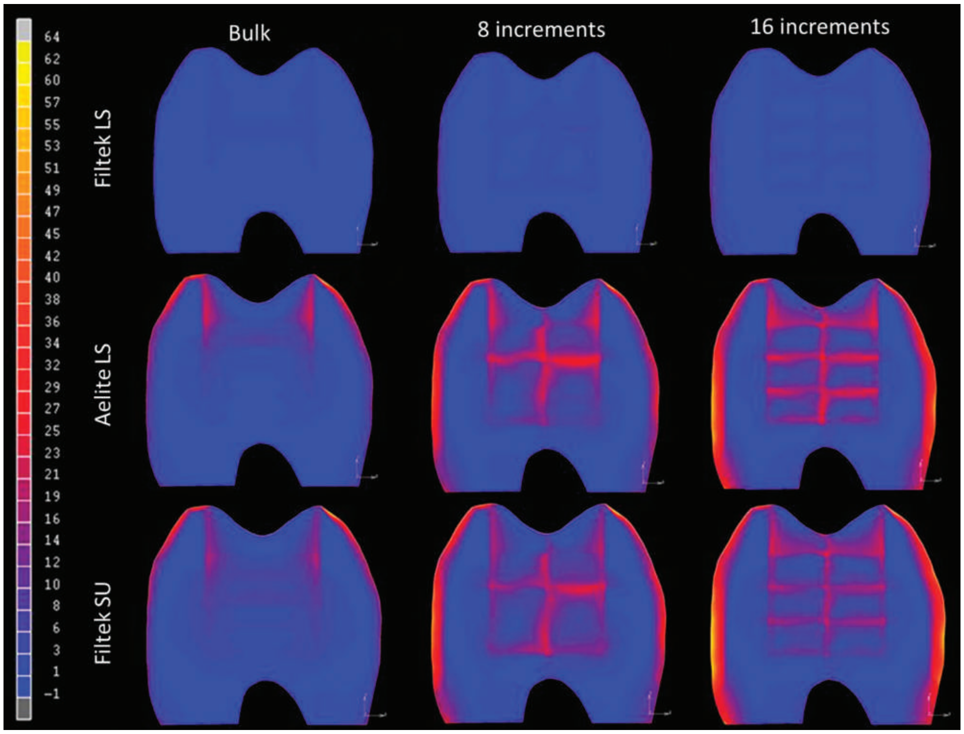

Figure 1. *Stress distributions calculated by finite element analysis (modified von Mises equivalent stresses, MPa).*

Pearson correlation tests were performed between elastic modulus, post-gel shrinkage, experimental bond strength, cuspal deformation determined experimentally and by FEA, stress in enamel, and stress along the restoration interface ($p<0.05$). The mean values of the 5% highest stress and strain were determined for the cervical enamel (where the strain gauges were fixed in laboratory tests). These values were used to calculate Pearson correlations with cuspal deformation by strain gauges. Furthermore, strain values were obtained at nodes of the buccal external surface corresponding to the same position where the strain gage was fixed in laboratorial tests. The stress values at the interface between composite resin and dentin were obtained corresponding to five depths of the restoration in 2D model and correlated with elastic modulus and post-gel shrinkage values in the five depths of the restoration of laboratorial tests. The mean values of the 5% highest stresses were determined for the dentin/composite interface and correlated with microtensile bond strength values.

RESULTS

Post-gel Shrinkage

The mean values and standard deviations for the post-gel shrinkage of three composites are presented in Table 2. One-way ANOVA revealed statistical difference among the composites ($p<0.001$). Filtek Supreme had the highest mean volumetric shrinkage value and Filtek LS had the lowest value.

Finite Element Analysis

Stress distributions for all groups are shown in Figure 1 and values of stress and strain obtained by finite element analysis for buccal cuspal and lingual cuspal are shown in Table 3. Compared to the other two composite resins, the Filtek LS restored teeth were least influenced by filling technique. The bulk filling technique resulted in lower stresses at the enamel/composite interface than the 2.0-mm increment technique, and the 2.0-mm techniques was lower than the 1.0-mm increment technique for Filtek Supreme and Aelite LS Posterior. The Aelite LS Posterior composite resulted in the highest stress values, while Filtek LS generated the lowest stress values along both enamel and dentin interfaces, irrespective of restorative technique. The 1.0-mm increment technique resulted in a substantial stress

Table 2: *Mean (SD) Volumetric Post-gel Shrinkage**

Composite Resins	Volumetric Post-gel Shrinkage,%
Filtek LS	0.11 (0.03)^{A}
Aelite LS Posterior	0.51 (0.02)^{B}
Filtek Supreme	0.62 (0.09)^{C}

** Different uppercase letters indicate significant difference between the composites (p<0.05).*

Table 3: *Values of Stress and Strain Obtained by Finite Element Analysis (FEA) for Buccal Cuspal (B) and Lingual Cuspal (L)*

Composite Resin	Bulk Filling						8 Increments						16 Increments					
	FEA Stress		FEA Strain		FEA Interface		FEA Stress		FEA Strain		FEA Interface		FEA Stress		FEA Strain		FEA Interface	
Depth	(B)	(L)	(B)	(L)	(B)	(L)	(B)	(L)	(B)	(L)	(B)	(L)	(B)	(L)	(B)	(L)	(B)	(L)
Filtek LS																		
4.5	3.7	4.1	21.8	21.1	1.5	1.53	3.5	4.96	20.91	25.97	1.46	1.66	5.14	4.8	30.63	24.79	1.56	3.7
3.5	3.7	3.4	23.4	24.9	1.3	1.31	5.12	4.79	31.75	35.46	1.53	1.52	7.32	4.93	46.49	36.85	2.00	3.7
2.5	2.1	3.1	15.8	22.9	1.7	1.64	4.36	7.75	34.07	60.05	1.73	1.66	5.51	8.09	43.85	63.13	1.58	2.1
1.5	1.7	2.1	13.1	15.8	1.9	1.84	5.27	8.84	42.67	69.88	2.26	1.95	7.06	9.54	58.09	75.96	1.70	1.7
0.5	1.8	1.9	13.6	14.8	1.3	1.31	5.85	8.42	46.04	67.84	1.56	1.47	9.25	10.32	73.49	83.49	2.03	1.8
Aelite LS Posterior																		
4.5	21.8	23.5	131.8	124.7	13.4	13.71	18.96	29.21	113.05	153.9	13.28	14.53	30.82	29.38	183.65	152.19	12.35	21.8
3.5	20.4	17.9	130.8	132.2	14.0	13.67	27.18	26.82	167.79	198.78	14.88	14.54	43.22	29.29	274.88	219.65	15.61	20.4
2.5	11.8	18.2	92.2	138.6	11.2	10.47	23.24	42.06	181.42	325.83	11.47	10.86	32.46	47.91	258.61	374.61	11.56	11.8
1.5	10.7	14.2	85.9	111.0	5.7	5.56	26.98	45.71	217.87	361.51	17.12	14.84	41.32	56.15	340.03	447.77	14.93	10.7
0.5	11.1	11.7	87.2	93.9	3.7	3.5	28	40.42	220.68	326.2	10.21	9.40	52.51	58.84	417.72	476.91	13.74	11.1
Filtek Supreme																		
4.5	22.8	24.9	136.1	129.6	9.3	9.74	21.57	30.87	128.68	161.96	10.25	11.53	34.23	32.22	203.83	166.49	11.12	22.8
3.5	23.3	20.9	147.3	152.3	8.8	8.62	31.09	29.24	192.62	216.55	11.02	10.90	48.15	32.66	306.28	244.45	14.45	23.3
2.5	13.4	19.9	103.4	150.3	11.3	10.73	26.28	46.72	205.21	361.71	11.01	10.55	35.69	52.74	284.21	411.81	12.50	13.4
1.5	11.6	14.5	90.8	111.2	8.5	8.34	31.14	52.42	251.41	414.38	14.48	12.15	44.74	60.98	367.95	485.81	12.44	11.6
0.5	11.6	12.0	88.8	94.7	5.78	5.67	33.38	48.86	262.51	393.63	10.06	9.21	57.06	63.86	453.62	517.17	10.54	11.6

increase at the external tooth surface, particularly in the cervical enamel region, compared to the bulk and 2.0-mm increment techniques.

Correlations Between Experimental and FEA Results

Figures 2 and 3 compare cuspal deformation obtained with strain gauges in the laboratory study and strains obtained with the FEA in the same region of enamel on buccal and lingual surfaces. Cuspal deformation values from the laboratory study were very similar to the deformation values calculated by FEA (r=0.946).

The values of strain and stress by finite element models and Pearson correlations between various parameters are shown in Table 4. Significant linear correlations were found among the following parameters ($p<0.05$): elastic modulus values and FEA strain, elastic modulus and FEA stress, post-gel shrinkage and FEA strain, post-gel shrinkage and FEA stress, FEA strain and FEA stress, cuspal strain measured by strain gauges and FEA strains, and cuspal strain measured by strain gauges and FEA stress. No significant correlations were found between elastic modulus and cuspal deformation measured by strain gauge, post-gel shrinkage and cuspal deformation measured by strain gauge, and FEA stresses along the interface and the microtensile bond strengths. The stress values used were the 5% stress, cervical stress, and top/bottom stress.

DISCUSSION

The results of the present study confirmed that the magnitude and distribution of residual shrinkage stresses in the restoration/tooth complex depended on the composite material's post-gel shrinkage and elastic modulus as well as the filling technique used.

To calculate the shrinkage stresses, polymerization shrinkage behavior must be modeled. Since not all shrinkage generates stresses, a "post-gel" shrinkage value was used in the analysis. Post-gel shrinkage was defined as the portion of the total polymerization shrinkage that causes stresses, and was measured using the strain gauge technique.[23] The post-gel shrinkage of Filtek LS (0.11% by volume) was almost five times lower than that of Aelite LS Posterior (0.51%) and six times lower than that of Filtek Supreme (0.62. The low post-gel shrinkage values of Filtek LS could be explained by the silorane molecules, which have a siloxane core with four oxirane rings attached, that open during polymerization to link to other monomers. The oxirane ring opening causes volumetric expansion that partially compensates the shrinkage from

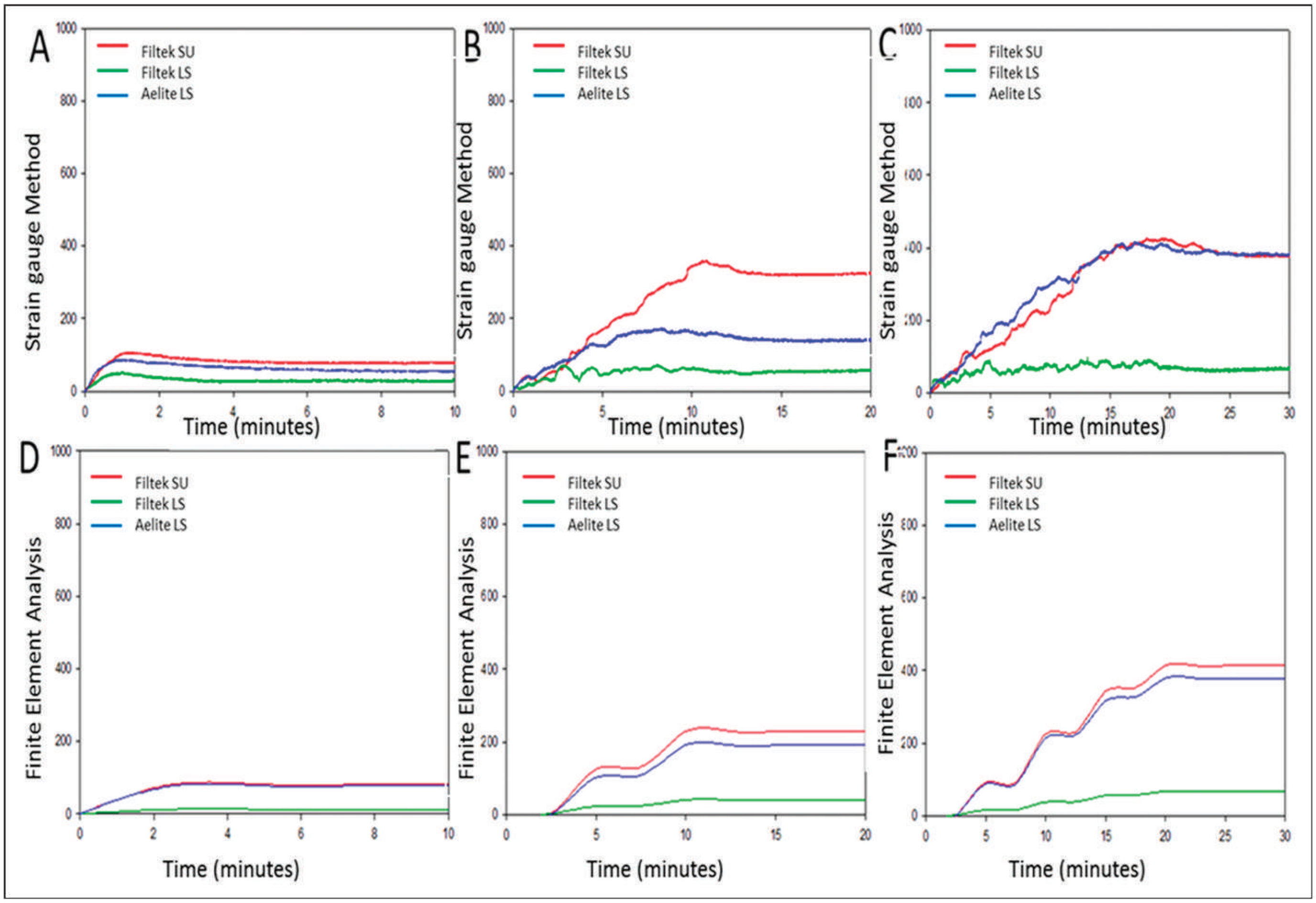

Figure 2. *Cuspal deformation at buccal cusp. (A): Bulk filling, strain gauge method. (B): 8 increments, strain gauge method. (C): 16 increments, strain gauge method. (D): Bulk filling, finite element analysis. (E): 8 increments, finite element analysis. (F): 16 increments, finite element analysis. A, B, and C are data from the laboratory study in Part I of this study.*[19]

molecular union.[12,24] Although both Aelite LS Posterior and Filtek Supreme have a Bis-GMA–based matrix, the Aelite LS Posterior had a lower post-gel shrinkage value than Filtek Supreme. This may be due to the higher filler loading of Aelite LS Posterior. A higher filler content means less volume of the resin matrix, and thus less composite shrinkage.[25] However, before interpreting this lower shrinkage to mean a lower shrinkage stress, it is important to also take into account that increasing filler content generally results in an increased elastic modulus,[25] and thus higher rigidity of a restoration, which in turn tends to increase shrinkage stresses.

Shrinkage stress is thus not only determined by the polymerization shrinkage, but is dependent on the combination of physical properties as well as structural features. Part I of this study covered the experimental components. Experimental tests are fundamental for the assessments of dental structures and restorative materials because they already naturally combine all relevant factors that determine a mechanical response to polymerization shrinkage. However, experimental studies also have limitations, such as their inability to obtain information about the internal behavior of a restoration and the determination of stresses. FEA was developed as an engineering tool to solve stress-strain conditions in complex structures while taking into account the interaction of the various factors, including linear and nonlinear effects caused by deformations and material properties. FEA has become a vital element in any comprehensive evaluation of complex stress conditions inside restored teeth.[3] This study used 2D analysis to study the stress distributions and deformations by assuming a plane strain condition in the tooth structure. This means that we could calculate the three-dimensional (3D) stress condition in a 2D geometric model. Simplification into a 2D geometry has the advantage of immediate insight and relatively

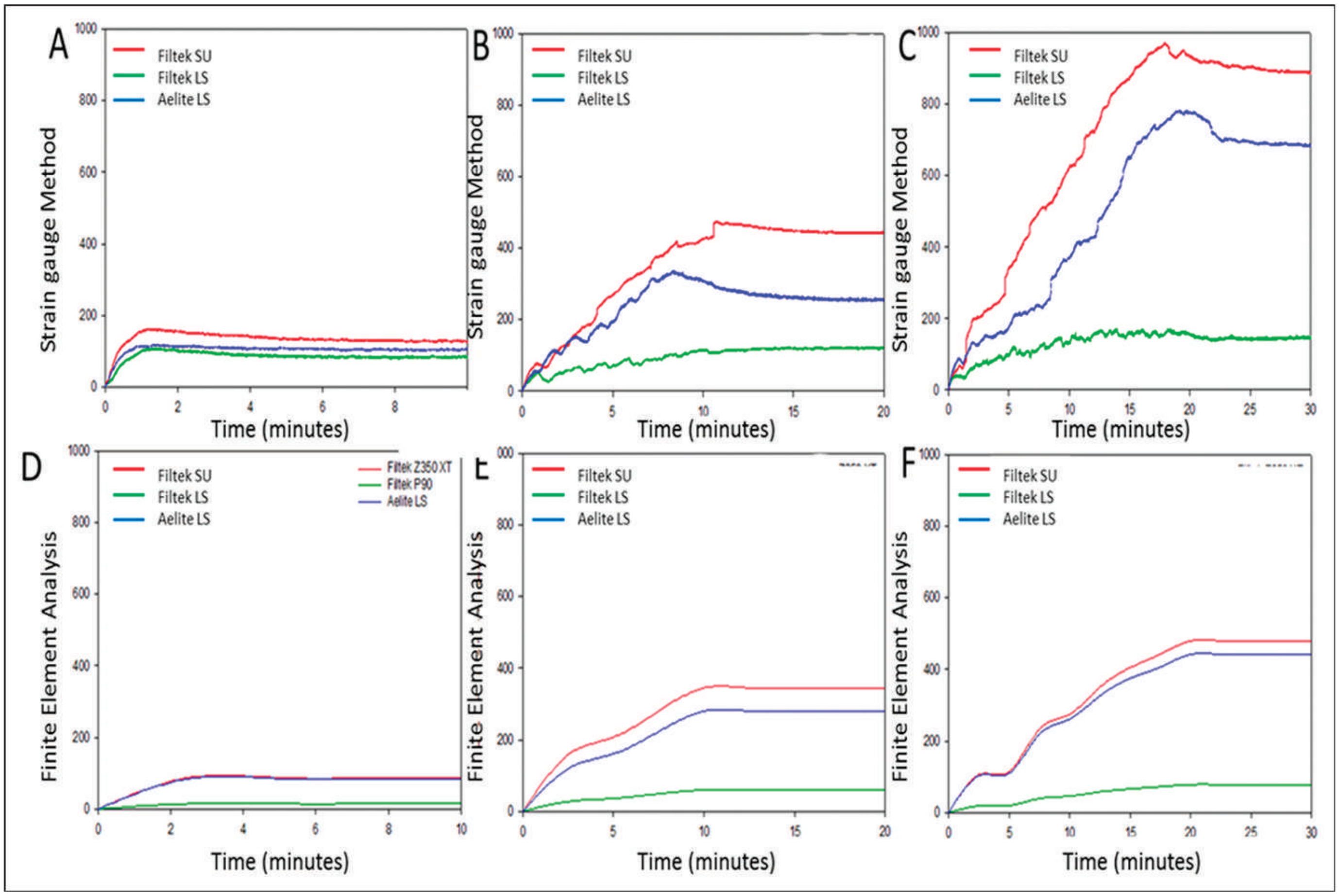

Figure 3. *Cuspal deformation at lingual cusp. (A): Bulk filling, strain gauge method. (B): 8 increments, strain gauge method. (C): 16 increments, strain gauge method. (D): Bulk filling, finite element analysis. (E): 8 increments, finite element analysis. (F): 16 increments, finite element analysis. A, B, and C are data from the laboratory study in Part I of this study.*[19]

affordable operating costs in modeling and analysis time, while the definition of the stress conditions can still provide significant insight into the 3D stress state. Stresses in three dimensions were integrated into one scalar value by using a modified von Mises criterion to represent the overall stress condition that could be used to show areas with most critical stress concentrations.[26] To ensure that the geometric

Table 4: *Pearson Correlations*

Correlations	*r*	*p*
Elastic modulus[a] × FEA strain	0.726*	0.027
Elastic modulus[a] × FEA stress	0.721*	0.028
Elastic modulus[a] × cuspal deformation by strain gauge[a]	0.567	0.111
Post-gel shrinkage × FEA strain	0.780*	0.013
Post-gel shrinkage × FEA stress	0.798*	0.010
Post-gel shrinkage × cuspal deformation by strain gauge[a]	0.616	0.077
FEA strain × cuspal deformation by strain gauge[a]	0.946*	0.000
FEA stress × cuspal deformation by strain gauge[a]	0.978*	0.000
FEA stress along interface × microtensile bond strength[a]	0.194	0.441

Abbreviations: FEA, finite element analysis.
[a] *Values determined in Part I of this study.*[19]
* *Significant correlations between study factors ($p<0.05$).*

(plane strain) simplification was justified, we validated the FEA results with strain gauge experiments. The validation confirmed that despite the simplifying assumptions, the general response of the FEA models was realistic. The comparison showed a high correlation between the strains calculated by FEA and measured by strain gauges (0.946), and between the stress calculated by the FEA and the strain measured by strain gauges (0.978). These findings validated our 2D analysis.

The validity of our assumptions about the material properties, tooth and cavity geometry, and artificial constraints in the simulation of the restored teeth was tested by comparing the FEA strain outcomes with the experimental strain results obtained in Part I of this study. Although the calculated stresses could not be validated directly from the laboratory experiments, they could be verified indirectly from the deformation and its consequences.[3] In our study, cuspal strains calculated by the FEA were similar to the cuspal strain data collected experimentally using strain gauges placed on cuspal surfaces (Figures 2 and 3). This close similarity supports the validity of our FEA models and stress results.[26]

In the FEA results (Figure 1), among the three composites, the tooth restored with Filtek LS showed the lowest stress concentrations for all restorative techniques. The performance of Filtek LS can be attributed to its low elastic modulus and low post-gel shrinkage. The low post-gel shrinkage demonstrated by Filtek LS is desirable. On the other hand, a low elastic modulus may be indicative of higher wear rates in areas subjected to masticatory forces.[27,28] Aelite LS Posterior (marketed as a low-shrink composite) and Filtek Supreme (which can be considered conventional with respect to polymerization shrinkage) showed stress concentrations at the base of the cusps. Although the post-gel shrinkage of Aelite LS Posterior was 18% lower than that of the Filtek Supreme, its higher elastic modulus (up to 60%) resulted in similar residual shrinkage stresses. The higher elastic modulus of Aelite LS Posterior can be attributed to its higher filler volume compared to Filtek Supreme.[14] The effect of this balance between post-gel shrinkage and elastic modulus may explain the similar performance of Filtek Supreme and Aelite LS Posterior. These results were consistent with values reported by Boaro and others.[25] Reduction of the number of the increments by using a larger volume of composite in each increment resulted in lower residual shrinkage stresses and lower cuspal deformation strains. This restorative protocol may reduce clinically undesirable effects of shrinkage stress, such as cracks, debonding, and postoperative sensitivity. According to Part I of this study, a decrease in the number of increments from 1.0 mm to 2.0 mm did not compromise the bonding performance or the quality of the polymerization, and could thus improve the overall conditions for the clinical longevity of the restoration.

All stresses and strains that the FEA calculated in the tooth and composite materials showed a significant positive correlation with elastic modulus, post-gel shrinkage, and the measured cuspal deformation. Other studies also found that stresses generated by polymerization increase with increasing composite elastic modulus.[10,27,28] The elastic modulus is an important material property that describes the relationship between stress and strain. Materials with high elastic modulus deform less when they are stressed. Thus, when polymerization contraction ("deformation") is restricted by bonding to the cavity walls, a composite with a high elastic modulus will result in higher shrinkage stress than if the composite would have had a low elastic modulus. This effect can be observed in experimental studies where high-compliance devices tend to overestimate the shrinkage stresses.[28-30] The positive correlation between stress and post-gel shrinkage was also consistent with reports in other studies.[23] Weaker correlations were found between the strains measured by the strain gauges and the elastic modulus or post-gel shrinkage values. This might be due to the cumulative effect of experimental variations, which were less when involving FEA analysis. We found no correlation between stress values along the tooth/composite interface determined by the FEA and the bond strength measured by microtensile tests at different cavity depths. This may not be unexpected because the FEA determined the stresses at the interface, not the strength at the interface. Strength is a property that is likely affected by multiple factors. Often shrinkage stress is considered to be one of those factors.[31-34] However, no evidence was found in this analysis, while the results of Part I also showed no statistically significant differences in bond strengths between composites with different post-gel shrinkage values.

This two-part study showed that the quality of bond and mechanical properties can be challenged in large composite restorations by compromised curing, high cuspal deflection, and unfavorable stress distribution in the remaining tooth structures. To select the composite resin material and filling technique for restoring large cavities, clinicians should try to combine good mechanical properties with lower shrinkage stress. Bulk filling is not a favorable technique to restore large cavities because it may negatively affect the cure and therefore reduce mechanical properties. On the other hand, a 16 increment technique (1-mm) would cause higher residual shrinkage stresses and higher cuspal strains. The cusp flexure results in Part I of this study and the stress analysis performed in Part II demonstrated that an incremental technique using larger rather than smaller increments (approximately 2 mm high) may provide the best balance between adequate mechanical properties, represented by elastic modulus, Vickers hardness, bond strength, ultimate strength, and lower residual shrinkage stresses.

Although FEA was essential to assess the stress conditions, the validity of stress calculations depends on the correct input of material properties, anatomic shape, and restraints of the restored tooth structure. Most of these input variables must be obtained from laboratory tests. Since laboratory tests are often unable to provide all needed input variables for the finite element analysis, which then have to be estimated, simulation experiments remain necessary to validate the stress calculations. A validated finite element model can be further used to predict mechanical failures or investigate questions that cannot be accessed as well in laboratory tests.[16]

CONCLUSIONS

When restoring a tooth with large cavity, increasing the number of increments and using materials with high post-gel shrinkage and elastic modulus values resulted in higher stresses in the remaining tooth structure and at the tooth/restoration interface. The combination of a low post-gel shrinkage composite and a technique that appropriately polymerized the restoration, such as increments that are large enough but not exceeding 2-mm thickness, can minimize the negative effects of residual shrinkage stresses without impairing the mechanical properties of composites. Cuspal strain measured by strain gauges validated and was validated by the finite element analysis. The validation and correlation of experimental and computational methods is an important step in a comprehensive research approach and is essential to justify conclusions drawn from *in vitro* analyses.

Acknowledgements

This study was supported by grants from CNPq and FAPEMIG.

Conflict of Interest

The authors have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 25 June 2013)

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