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Influence of the Compliance and Layering Method on the Wall Deflection of Simulated Cavities in Bulk-fill Composite Restoration

Y-J Kim • R Kim • JL Ferracane • I-B Lee

Clinical Relevance

Both conventional and bulk-fill composites showed lower wall deflection when incrementally filled. Restoration by bulk filling with high viscous bulk-fill composites cannot achieve the reduction in the wall deflection of simulated cavities comparable to those obtained with incremental layering of conventional universal composites.

SUMMARY

The aim of this study was to investigate the effects of the layering method and compliance on the wall deflection of simulated cavities in bulk-fill and conventional composite restorations and to examine the relationships between the wall deflection and the polymerization shrinkage, flexural modulus, and polymerization shrinkage stress of composites. Six light-cured composites were used in this study. Two of these were conventional methacrylate-based composites (Filtek Z250 and Filtek Z350 XT Flowable [Z350F]), whereas four were bulk-fill composites (SonicFill, Tetric N-Ceram Bulk-Fill, SureFil SDR Flow [SDR], and Filtek Bulk-Fill). One hundred eighty aluminum molds simulating a mesio-occluso-distal cavity (6 W×8 L×4 D mm) were prepared and classified into three groups with mold wall thicknesses of 1, 2, and 3 mm. Each group was further subdivided according to the composite layering method (bulk or incremental layering). Linear variable differential transformer probes were used to measure the mold wall deflection of each composite (n=5) over a period of 2000 seconds (33.3 minutes). The polymerization shrinkage, flexural modulus, and polymerization shrinkage stress of the six composites were also measured. All groups with bulk filling exhibited significantly higher deflection compared with groups with incremental layering. The deflection decreased as mold wall thickness increased. The highest and lowest polymerization shrinkage stresses were recorded

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DOI: 10.2341/15-260-L

for Z350F (5.07 MPa) and SDR (1.70 MPa), respectively. The correlation between polymerization shrinkage and the mold wall deflection decreased with increasing wall thickness. On the other hand, the correlation between flexural modulus and the mold wall deflection increased with increasing wall thickness. For all groups, wall deflection correlated strongly with polymerization shrinkage stress.

INTRODUCTION

The polymerization shrinkage stress of dental composites may compromise the bond integrity and cause enamel cracking and cusp deflection.[1] Therefore, minimizing polymerization shrinkage stress of composites is still a major challenge for dental clinicians when placing composite restorations.

Incremental layering can reduce the effects of the configuration-factor, thereby allowing more flow of the composite from the free surface, which also reduces the volume of composite being cured, maximizes the degree of conversion, and increases the adaptation to cavity walls.[2-4] Although incremental layering does have apparent benefits, the process of multiple layering and curing is time consuming; moreover, the effectiveness of this strategy in reducing polymerization shrinkage stress and cusp deflection has been questioned.[5-8] However, a number of studies have reported considerably reduced cusp deflection by using incremental layering compared with bulk filling.[4,9,10]

To predict polymerization shrinkage stress in the clinical situation, experiments must be designed in a way that mimics the tooth/composite interface.[11] Cusp deflections are well described to be closely related with polymerization shrinkage stress.[12] Moreover, cusp deflections have been extensively investigated using a variety of techniques and instruments, including the strain gage[13] and the linear variable differential transformer (LVDT) methods.[9]

Cusp compliance is an important factor that affects cusp deflection. Compliance is defined as a change in dimension of a system to unit force and has opposite meaning to stiffness. Thus, to obtain clinically relevant results, cusp compliance should be similar to that observed in clinical situations. Several studies have reported that teeth with cavities exhibit relatively high compliance.[9,14,15] The stress values measured in low compliance systems have ranged from 4 to 25 MPa,[3,16-18] whereas values obtained in high compliance systems have barely exceeded 5 MPa.[19,20]

In this study, aluminum blocks with a differing thickness of mold wall were used for reducing the substrate variation. The elastic modulus of aluminum is 68.5 GPa, which is within the range of tooth enamel (84.1 GPa) and dentin (18.5 GPa).[10] In a previous study, the cusp compliance of natural teeth with mesio-occluso-distal (MOD) cavities (1.5 W $\times$ 2 D and 3 W $\times$ 2 D mm) was 2.96 and 3.32 μm/N, respectively, which is about three to four times more than that of aluminum blocks.[21] Therefore, although the aluminum block does not exactly replicate the natural tooth, this experimental design enables the investigation of the cusp deflection under the conditions with minimized variables.

Recently, many bulk-fill composites have been introduced as alternatives to conventional composites. These composites are intended to be placed and bulk-cured in one increment, up to 4 to 5 mm in depth, either with or without a superficial capping layer. The rheological properties of these composites can be varied by modifying the filler content, monomer type, or by adding modulators to slow the polymerization rate.[22-24] However, little information is available regarding the polymerization kinetics of these composites. Moreover, no study to date has investigated the effect of cusp compliance and layering method on cusp deflection of bulk-fill composite materials or the relationship between cusp deflection and the polymerization shrinkage kinetics of these composites.

The aim of this study was to investigate the effects of the layering method and compliance on the wall deflections of simulated cavities in bulk-fill vs conventional composite restorations. In addition, the relationships between the wall deflection and the polymerization shrinkage, flexural modulus, and polymerization shrinkage stress of various composites were also examined.

METHODS AND MATERIALS

Materials

Six light-cured composites were examined in this study. Each composite was categorized as conventional or bulk-fill and high-viscosity or low-viscosity (flowable) composite according to its use and viscosity. Two were conventional methacrylate-based composites, a high-viscosity (Filtek Z250 [Z250]) and a flowable (Filtek Z350 XT Flowable [Z350F]) composite. The four bulk-fill composites included two high-viscosity composites (SonicFill

Table 1: *Brand Name, Type, Composition, and Manufacturer of Each Composite Used in This Study*

Composite (code, shade, batch no.)	Type	Composition	Manufacturer
Filtek Z250 (Z250, A2, N482264)	C, H	Bis-GMA, Bis-EMA, TEGDMA, UDMA 0.01-3.5 μm Zr/silica particles (82 wt%/60 vol%)	3M ESPE, St. Paul, MN, USA
SonicFill (SF, A2, 5026722)	B, H	Bis-GMA, TEGDMA, EBPDMA, silica, glass, oxide (83.5 wt%/69 vol%)	Kerr, Orange, CA, USA
Tetric N-Ceram Bulk-Fill (TNB, IVA, S09719)	B, H	Bis-GMA, UDMA Ba-glass filler, ytterbium trifluoride, Mixed oxide prepolymer (79-81 wt%/-)	Ivoclar Vivadent, Schaan, Liechtenstein
Filtek Z350 XT Flowable (Z350F, A2, N50234)	C, F	Bis-GMA, Bis-EMA, TEGDMA 5-20 nm Zr/silica nano-particles, 0.6-1.4 μm nano-clusters (65 wt%/-)	3M ESPE, St. Paul, MN, USA
SureFil SDR Flow (SDR, Universal shade, 130630)	B, F*	Modified UDMA, TEGDMA, EBPDMA Ba-Al-F-B-Si glass, St-Al-F-Si glass (68 wt%/45 vol%)	Dentsply, Konstanz, Germany
Filtek Bulk-Fill Flowable (FB, A2, N540884)	B, F*	Bis-GMA, UDMA, Bis-EMA, Procrylat resins Zr/silica, ytterbium trifluoride (64.5 wt%/42.5 vol%)	3M ESPE, St. Paul, MN, USA

Abbreviations: B, bulk-fill; Bis-EMA, bisphenol-A polyethylene glycol diether dimethacrylate; Bis-GMA, bisphenol-A diglycidyl ether dimethacrylate; C, conventional composite; EBPDMA, ethoxylated bisphenol-A-dimethacrylate; F, flowable; H, high-viscosity; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.
** Bulk-fill composites requiring a 2-mm capping layer as recommended by manufacturers.*

[SF]/Tetric N-Ceram Bulk-Fill [TNB]) and two flowable composites (SureFil SDR Flow [SDR]/ Filtek Bulk-Fill [FB]). The brand names, types, compositions, and manufacturers of the composites are listed in Table 1. An LED light unit (Elipar S10, 3M ESPE, St. Paul, MN, USA) was used for curing; the light irradiance exiting the tip (9.9 mm in diameter) was 1200 mW/cm^2.

Measurement of Deflection of Aluminum Mold Wall

One hundred eighty aluminum molds simulating an MOD cavity (6 W × 8 L × 4 D mm) were prepared and allocated into three groups with varying thicknesses of the wall of aluminum mold (1, 2, and 3 mm; Figure 1A). The inside wall of each cavity was air abraded with 50 μm Al_2O_3 powder, rinsed with water, and air dried. Then, the inside of the cavity was coated twice

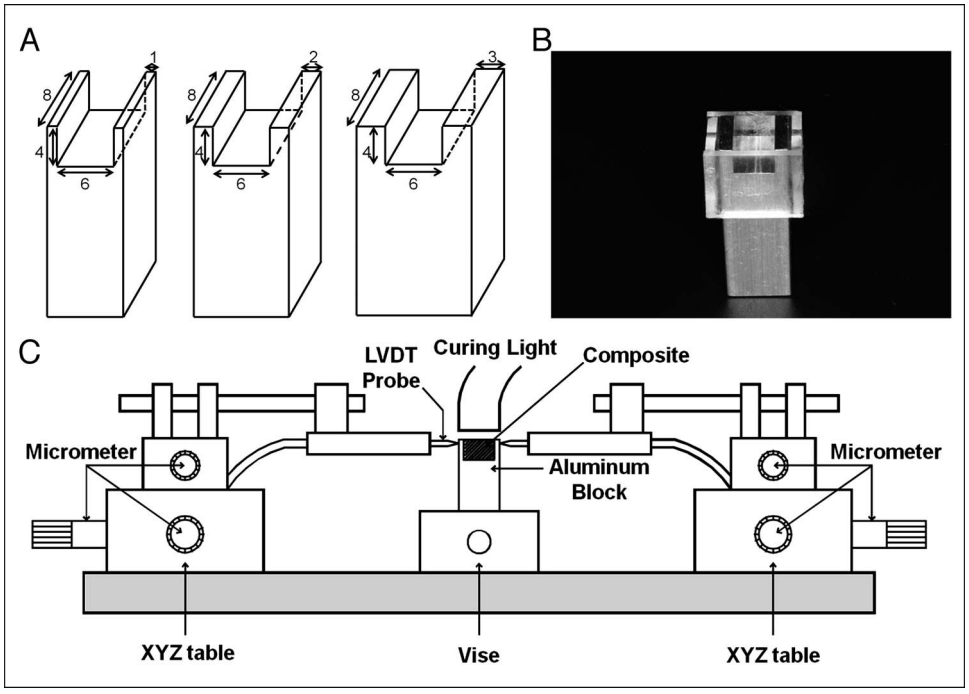

Figure 1. *(A) Dimensions (mm) of aluminum blocks with varying mold wall thicknesses: left, 1 mm; center, 2 mm; right, 3 mm. (B) Acrylic cap placed over the aluminum block. (C) Instrument for measuring mold wall deflection.*

with a metal primer (Z-Prime Plus, Bisco, Schaumburg, IL, USA) and dried. A thin layer of Scotchbond Multipurpose Adhesive (3M ESPE) was applied and light cured for 10 seconds.

An acrylic cap (Figure 1B) with two notches on the top of the lateral wall was fabricated and placed on top of the aluminum block to prevent the composite from being pushed out of the mold during layering. The acrylic cap was also used to place the LVDT probes precisely 1 mm below the upper surface of mold wall through the notches of the acrylic cap. The inner surface of the acrylic cap was lubricated with petroleum jelly to prevent the composite from adhering. The required weight of composite to fill the aluminum mold was calculated from the density of the composite and the volume of the mold, and the appropriate amount of composite was weighed before use.

The groups with different mold wall thickness were further subdivided according to composite layering method (bulk vs incremental layering). Before mounting the specimen in the mold wall deflection measurement instrument, the composite for bulk filling or the first layer of incremental filling was placed in the mold. In the bulk-filling group, the composite was light cured from the upper surface for 20 seconds, the mesially tilted upper side for 20 seconds, the distally tilted upper side for 20 seconds, and again the upper surface for 20 seconds (total 80 seconds to be consistent with the energy delivery for the incremental layering group). For the incremental layering group, the composite was filled in four horizontal increments approximately 1 mm thick. Each layer was light cured from the upper surface for 20 seconds (total 80 seconds) for maximum polymerization to minimize possible bias that could be caused by incomplete curing of composites. Five aluminum blocks were allocated for each subgroup (bulk or incremental) of each composite.

The displacement of the mold wall was measured in real time at 25 ± 0.5°C throughout the curing process using two LVDT probes (AX-1, Solartron Metrology, West Sussex, United Kingdom), each with a sensitivity exceeding 0.1 μm over a range of ±1 mm (Figure 1C). The displacement values measured by the two LVDT probes were stored on a computer using a data acquisition board (PCI-6024, National Instruments, Austin, TX, USA) and software (LabVIEW, National Instruments). Measurement of mold wall deflection was initiated 20 seconds prior to light irradiation to obtain a baseline and continued for up to 2000 seconds (33.3 minutes), at a rate of 2 data points/s. The displacements of both sides were added to obtain the total amount of deflection (n=5).

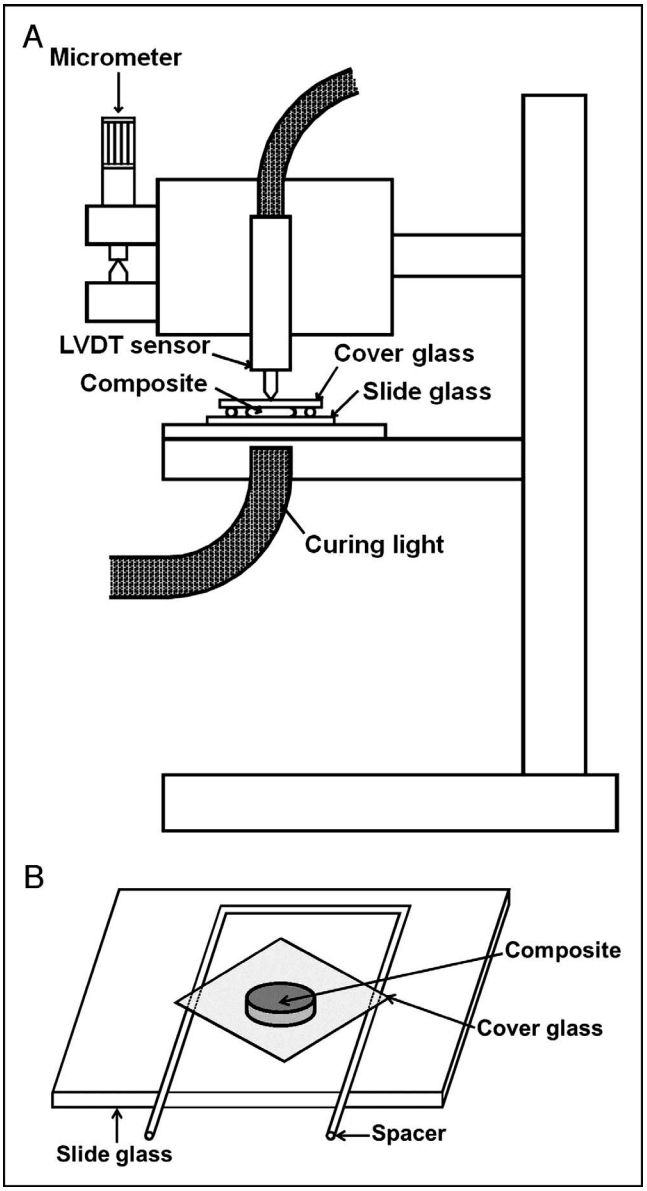

Figure 2. *(A) Instrument for measuring polymerization shrinkage using the modified bonded disc method. (B) Specimen preparation.*

Measurement of Axial Polymerization Shrinkage

Axial polymerization shrinkage was measured with the modified bonded disc method (Figure 2).[25] Briefly, the designated amount of composite was pressed between a slide glass and a flexible cover glass (Marienfeld-Superior, Lauda-Königshofen, Germany). A metal wire spacer was used to make 0.5-mm-thick specimens. The tip of an LVDT probe was placed on the cover glass at the center of the

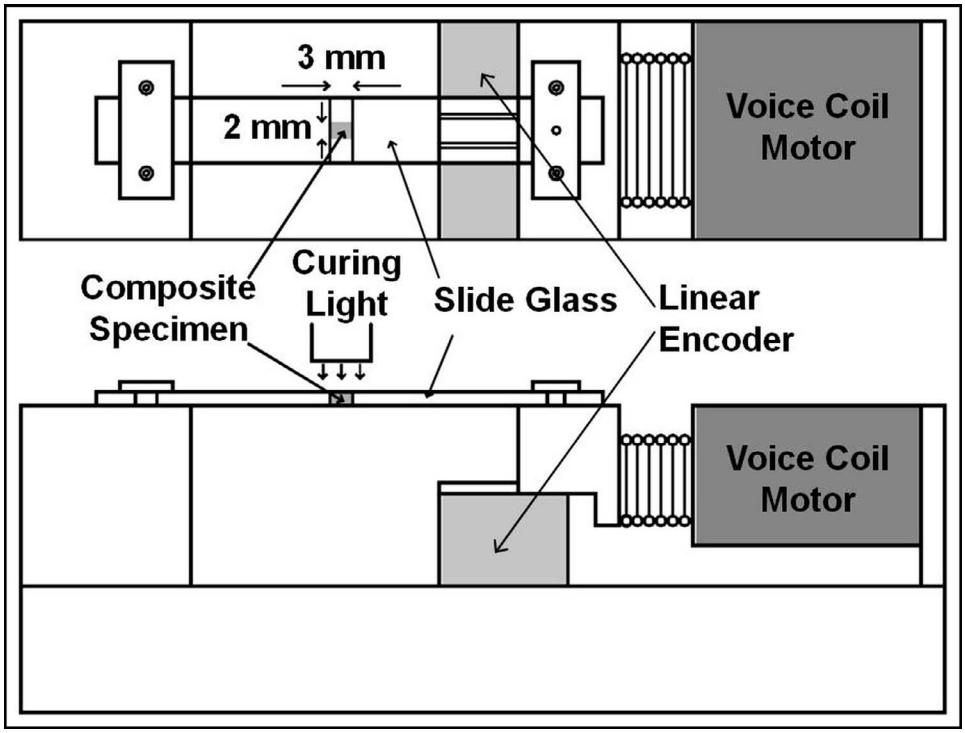

Figure 3. *Instrument for measuring polymerization shrinkage stress using a voice coil motor with feedback mechanism.*

disc-shaped composite specimen; this point was set to zero. Baseline data were obtained for 10 seconds and then the curing light was turned on for 40 seconds. The axial shrinkage data were stored on a computer at a rate of 10 data points/s for 600 seconds (n=5). The thickness of the light-cured specimen was measured using a micrometer. The axial polymerization shrinkage (%) was calculated using the following equation:

$$\text{Axial polymerization shrinkage}(\%) = \frac{100 \times \text{shrinkage}}{(\text{cured specimen thickness} + \text{final shrinkage})}$$

The shrinkage rate (%/s) and time at the peak shrinkage rate (seconds) were also obtained.

Measurement of Flexural Modulus

Bar-shaped specimens were generated by compressing the composite between a Teflon mold (3 W × 3 T × 30 L mm) and a slide glass. The specimens were divided into five parts and light cured with overlapping exposures of 40 seconds each (total 200 seconds). The cured specimens were polished and stored in dry conditions for 1 day in the dark at room temperature (25±1°C). The width and thickness of each specimen was measured with a micrometer; flexural modulus was measured using the three point bending method with a universal testing machine (LF Plus, Lloyd Instruments, West Sussex, United Kingdom) at a crosshead speed of 0.5 mm/min (supporting span length=20 mm; n=5).

Measurement of Polymerization Shrinkage Stress

A custom-made instrument with a voice coil motor (MGV52-20-0.5, Akribis Systems, Singapore) was used to measure the polymerization shrinkage stress (Figure 3). Briefly, a slide glass was fixed to a movable stage, which was connected to the voice coil motor. Another slide glass was fixed to an immobile stage on the opposite side of the motor. As the composite between the two slide glasses contracted due to polymerization, the slide fixed to the movable voice coil motor was pulled to the opposite slide, which was fixed on the immobile stage. This deviation was then detected by the linear encoder. Immediately, a servo amplifier provided electrical current to the voice coil motor to offset this deviation. Therefore, the distance between the two slide glasses was maintained. This feedback mechanism continued, with the servo electrical current staying proportional to the polymerization shrinkage stress. Calibration analysis revealed a linear relationship between the shrinkage force and the servo current.

The end surfaces of two 1-mm-thick slide glasses were sandblasted with 50-μm Al_2O_3 particles and covered with adhesive tape. A 2-mm-wide window

was created on the taped surface, thus exposing the glass surface, which was treated with silane (Monobond S, Ivoclar Vivadent, Schaan, Liechtenstein) and a bonding agent (Scotchbond Multipurpose Adhesive, 3M ESPE) and light cured for 10 seconds. The two slide glasses were aligned 3 mm apart from one another and then fixed on the movable and immobile stages of the instrument. The volume of the composite specimen between the two slide glasses was 6 mm^3. After the composite was placed between the slides, baseline data were obtained for 10 seconds, and the composite was irradiated with a curing light for 40 seconds. Measurements were made for each composite, at a rate of 10 data points/s, for 10 minutes (n=5).

Measurement of the Compliance of Aluminum Mold Wall

The aluminum block was fixed on a metal base and a weight loaded on the block 0.5 mm from the tip of the mold (Figure 4). Additional weight was applied onto the mold wall in increments of 1 to 5 kg. The mold wall displacements were measured using an LVDT probe, and the compliances were obtained from the measured load-displacement curves (n=3).

Statistical Analysis

Data were analyzed using SPSS software (version 21.0). Multiple-way analysis of variance (ANOVA) and Tukey's post hoc test were used to compare the deflection groups. The polymerization shrinkage, flexural modulus, and polymerization shrinkage stress of the composites were compared using one-way ANOVA and Tukey's post hoc tests. Pearson's correlation analysis was conducted to investigate the relationships between deflection and the polymerization shrinkage, flexural modulus, and polymerization shrinkage stress of the composites. All tests were conducted at α=0.05.

RESULTS

Mold Wall Deflection

The mold wall deflections of Z250 fillings of different thicknesses and layering methods as a function of time are shown in Figure 5. The majority of the deflection was observed within 500 seconds and gradually increased thereafter. The deflection occurred in a stepwise manner in the incremental layering group; moreover, deflection decreased slightly at the initiation of each period of light curing and increased thereafter. The mean deflections (micrometers) at 2000 seconds (33.3 minutes)

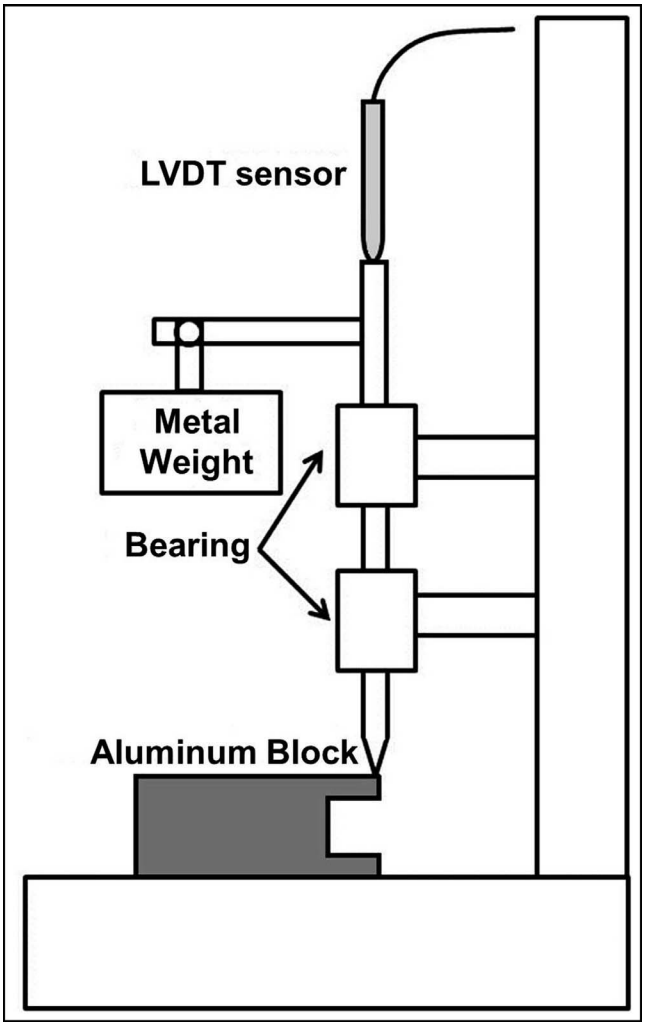

Figure 4. *Instrument for measuring the compliance of the aluminum blocks.*

for each composite are presented in Table 2. The highest and lowest deflections were obtained using Z350F bulk filling/1-mm mold wall thickness (51.0 μm) and SDR incremental layering/3-mm mold wall thickness (3.8 μm), respectively. The deflection (micrometers) and reduction (%) from bulk to incremental layering for each subgroup are presented in Figure 6. Mold wall thickness, layering method, and composite brand all yielded statistically significant differences ($p<0.05$) in the deflection. All groups with bulk filling exhibited significantly higher deflection compared with groups with incremental layering ($p<0.05$). Deflection decreased with increasing mold wall thickness ($p<0.05$).

Axial Polymerization Shrinkage

The Z350F composite demonstrated the highest polymerization shrinkage (3.52%), followed by FB

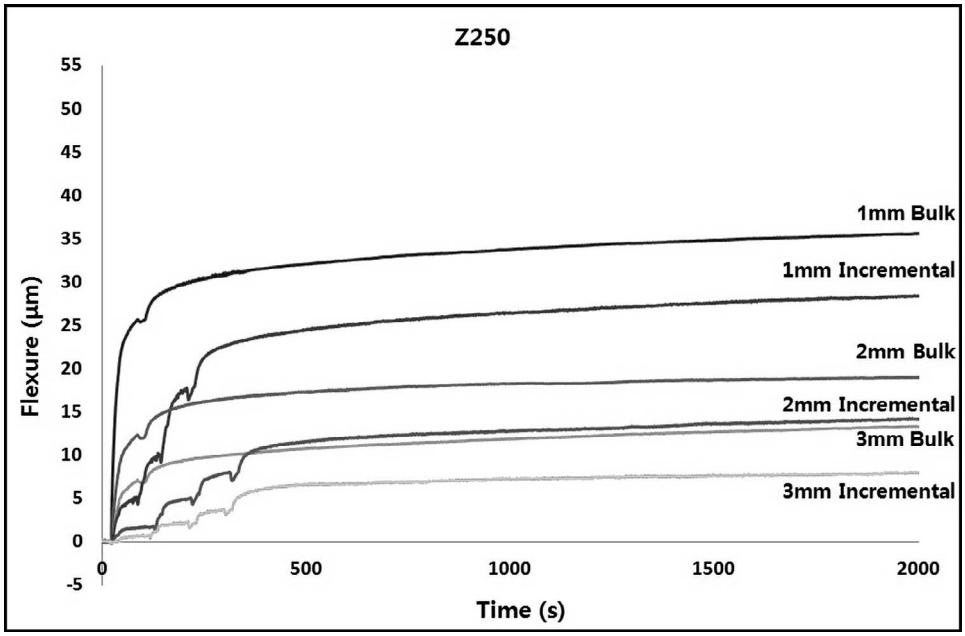

Figure 5. *The deflection (μm) of the Z250 composite with varying mold wall thicknesses and layering methods as a function of time.*

(3.17%), SDR (2.88%), Z250 (2.18%), and TNB (2.11%), whereas SF showed the lowest shrinkage (2.08%; Table 3). No significant differences were observed between Z250, TNB, and SF with respect to polymerization shrinkage ($p>0.05$). The polymerization shrinkage rates (%/s) and times at the peak shrinkage rate are shown in Table 3. The maximum rate of polymerization shrinkage was highest for SDR (0.64 %/s) and lowest for SF (0.34 %/s). The time at the peak shrinkage rate (seconds) was longest (2.11 seconds) for Z350F and shortest (1.11 seconds) for TNB.

Flexural Modulus

The flexural modulus (GPa) of each composite is presented in Table 3. Z250 showed the highest flexural modulus (9.20 GPa), followed by SF, TNB, Z350F, SDR, and FB (4.63 GPa). With the exception of Z350F and SDR ($p=0.888$), the composites exhibited significantly different flexural modulus values ($p<0.05$).

Polymerization Shrinkage Stress

The highest and lowest polymerization shrinkage stresses were recorded for Z350F (5.07 MPa) and SDR (1.70 MPa), respectively (Table 3). No significant differences were observed between Z250, TNB, and SF ($p>0.05$).

Compliance of Aluminum Mold Wall

The mold wall compliances with 1-, 2-, and 3-mm thicknesses were 0.81, 0.22, and 0.13 μm/N, respectively. The compliance decreased with increasing mold wall thickness.

Correlation Analysis

The correlation analysis results are presented in Table 4. For the 1-mm-thick mold, the deflection and polymerization shrinkage showed strong and moderate correlations in bulk ($r=0.706$) and incremental layering ($r=0.446$) groups, respectively. Meanwhile, for the 3-mm-thick mold, the deflection and flexural modulus were moderately correlated ($r=0.376$) in the bulk-filling group. The correlation between polymerization shrinkage and the deflection decreased as mold wall thickness increased. On the other hand, the correlation between flexural modulus and deflection increased with increasing mold wall thickness. The deflection for all groups correlated strongly with the polymerization shrinkage stress ($r=0.785$-0.969) and the product of shrinkage and modulus ($r=0.657$-0.780).

DISCUSSION

In this study, deflection was successfully simulated via micromechanical bonding of the composite to an aluminum block with a simulated cavity. Micromechanical bond strength of the composite to the aluminum surface was sufficient to produce measurable deflection as detected by LVDT probes. This idea is further supported by the lack of debonding spikes in the deflection curves. Therefore, our experimental design effectively simulated cusp de-

Table 2: *Mean Deflection (μm) for Each Group at 2000 Seconds (33.3 Minutes)*

Composite	Layering method	Aluminum mold wall thickness		
		1 mm	2 mm	3 mm
		Deflection, μm		
Filtek Z250	Bulk	35.6 (1.2)^{B,a}	19.0 (0.6)^{B,c}	13.4 (2.0)^{B,d}
	Incremental	28.4 (0.9)^{C,D,b}	14.2 (0.7)^{C,d}	8.1 (0.8)^{C,e}
SonicFill	Bulk	31.0 (0.6)^{C,a}	19.5 (1.7)^{B,c}	12.7 (1.4)^{B,d}
	Incremental	26.6 (1.9)^{D,b}	13.6 (1.2)^{C,d}	9.4 (0.7)^{C,e}
Tetric N-Ceram Bulk-Fill	Bulk	27.2 (0.7)^{D,a}	14.2 (0.7)^{C,c}	8.7 (0.7)^{C,d}
	Incremental	23.1 (0.8)^{E,b}	7.3 (0.5)^{D,e}	4.6 (0.1)^{D,f}
Filtek Z350 XT Flowable	Bulk	51.0 (2.2)^{A,a}	27.6 (2.0)^{A,b}	15.9 (1.1)^{A,d}
	Incremental	48.2 (1.2)^{A,a}	21.0 (1.7)^{B,c}	11.8 (0.3)^{B,e}
SureFil SDR Flow	Bulk	28.4 (1.5)^{C,D,a}	10.8 (1.1)^{D,c}	4.8 (0.2)^{D,e}
	Incremental	15.1 (0.6)^{F,b}	7.0 (0.8)^{D,d}	3.8 (0.3)^{D,e}
Filtek Bulk-Fill Flowable	Bulk	36.3 (2.0)^{B,a}	14.2 (1.3)^{C,c}	9.5 (0.3)^{C,d}
	Incremental	23.4 (0.8)^{E,b}	8.9 (0.7)^{D,E,d}	4.8 (0.8)^{D,e}

Identical uppercase letters: no significant difference among groups of the same wall thickness ($p>0.05$). Identical lowercase letters: no significant difference among groups of the same composite ($p>0.05$). Numbers in parentheses are standard deviations ($n=5$).

flection without the variability associated with natural teeth.

Bulk-fill composites can be classified into two types according to their viscosity and delivery method. Some low-viscosity bulk-fill composites (SDR and FB) necessitate a 2-mm capping layer with a conventional hybrid composite because of their low filler content and decreased abrasion resistance.[22] Another group of bulk-fill composites having high viscosity and filler content (SF and TNB) showed mechanical strength comparable to hybrid conventional composite, so they do not need to be capped with an additional layer.

The present study compared the polymerization shrinkage and related properties of four bulk-fill composites with those of two conventional composites. The polymerization shrinkages of flowable composites (Z350F, SDR, and FB) were higher than those of high-viscosity composites (Z250, SF, and TNB). However, the flexural modulus values of the composites exhibited the opposite trend as for polymerization shrinkage. These are expected based on the difference in filler amount.

Shrinkage stress can be directly influenced by instrument compliance.[26] In the shrinkage stress measuring system used in this study, the dimensional change of the composite specimen during polymerization was not measured at the very end of each glass slide, so it could be considered that this system was not fully rigid. Therefore, the use of a feedback mechanism minimized the compliance of the instrument, but did not totally eliminate it.

Polymerization shrinkage stress, as determined by both polymerization shrinkage and flexural modulus, showed complex results. Z350F exhibited the highest shrinkage stress value because it showed the highest shrinkage strain. Furthermore, Z250 showed the second highest shrinkage stress, perhaps because it had the highest flexural modulus. The bulk-fill flowable composites (SDR and FB) exhibited lower polymerization shrinkage stress due to their lower flexural modulus values, even though they exhibited higher polymerization shrinkage than the bulk-fill high-viscosity composites.[23,24] In contrast to the Z350F conventional flowable composite, the SDR contains the patented, modified urethane dimethacrylate monomer (849 g/mol). This monomer has a relatively high molecular weight, resulting in reduced polymerization shrinkage and stress by decreasing the number of reactive sites per unit volume. Meanwhile, FB excluded the monomer TEGDMA (286 g/mol), which has approximately half the molecular weight of the commonly added dimethacrylates such as Bis-GMA (512 g/mol).[27]

The polymerization shrinkage stress of each bulk-fill composite varied according to the viscosity of the material. The bulk-fill flowable composites (SDR and FB) exhibited lower polymerization shrinkage stress compared with the high-viscosity bulk-fill composites (SF and TNB). These results could be explained by the differences in filler loading, which result in different rheological properties. In the present study, a positive correlation between the flexural modulus and filler fraction was observed. The filler fractions of the bulk-fill composites according to the manufac-

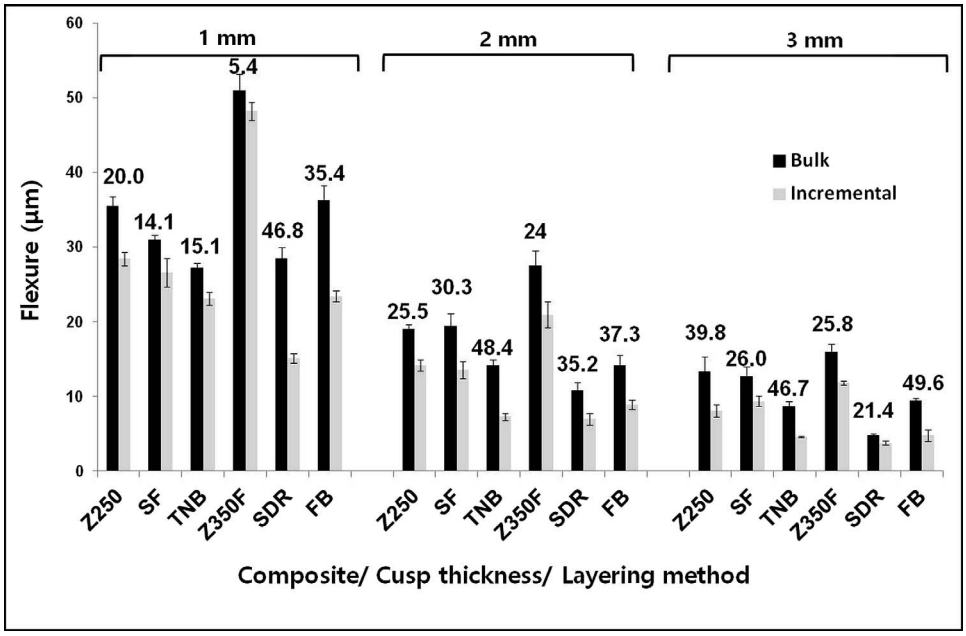

Figure 6. *Mean deflection (μm) and reduction in deflection from bulk to incremental layering (%) for each composite according to mold wall thickness and layering method. The number above each bar indicates the reduction (%) in deflection from bulk to incremental layering.*

turer's information are as follows: SF (83.5 wt%/69 vol%), TNB (79-81wt%/-), SDR (68.0 wt%/45 vol%), and FB (64.5 wt%/42.5 vol%); as expected, this order corresponds with that of the flexural modulus values.[16]

The deflection curves demonstrated slight reductions when the curing light was turned on, due to the thermal expansion effect created by the heat from the curing light (Figure 5). After the light curing unit was turned off, this expansion was counteracted by the ongoing polymerization shrinkage. In the bulk filling group, the thermal expansion effect could be observed only at the beginning of the final light curing, however, in the incremental layering group, four definite reductions in deflection due to thermal expansion effects could be clearly observed.[4]

Mold wall deflection decreased as wall thickness increased (compliance decreased) in all composite groups. However, considering the stiffness (inverse of compliance) of the wall, the thicker mold wall produced the higher stress. Incremental layering significantly reduced deflection compared with bulk filling for both conventional and bulk-fill composites (Table 2). These findings are in agreement with previous studies.[4,9,10] However, another study measured cusp deflection by using different curing techniques in natural teeth filled with conventional (Filtek Supreme Plus, 3M ESPE: bulk and incremental curing) or bulk-fill composites (X-tra fil, VOCO: bulk, incremental, and bulk/transtooth-illumination curing) and reported contradictory results.[28] The authors found no difference in cusp deflection between filling techniques within the same materials. These contradictory results may be due to that they used very thin cusp thickness with high compliance.

Table 3: *Polymerization Shrinkage (%), Maximum Shrinkage Rate (%/s), Time at Peak Shrinkage Rate (s), Flexural Modulus (GPa), and Polymerization Shrinkage Stress (MPa) of each Composite*

Composite	Polymerization shrinkage, %	Maximum shrinkage rate, %/s	Time at peak shrinkage rate, s	Flexural modulus, GPa	Polymerization shrinkage stress, MPa
Filtek Z250	2.18 (0.06)^{d}	0.35 (0.02)^{d}	1.56 (0.06)^{c}	9.20 (0.21)^{a}	2.88 (0.13)^{b}
SonicFill	2.08 (0.07)^{d}	0.34 (0.02)^{d}	1.79 (0.41)^{a,b,c}	7.97 (0.44)^{b}	2.73 (0.10)^{b}
Tetric N-Ceram	2.11 (0.02)^{d}	0.44 (0.03)^{c}	1.11 (0.11)^{d}	6.68 (0.25)^{c}	2.82 (0.13)^{b}
Filtek Z350 XT Flowable	3.52 (0.04)^{a}	0.64 (0.02)^{a}	2.11 (0.07)^{a}	5.79 (0.11)^{d}	5.07 (0.42)^{a}
SureFil SDR	2.88 (0.13)^{c}	0.64 (0.01)^{a}	1.67 (0.08)^{b,c}	5.62 (0.20)^{d}	1.70 (0.16)^{d}
Filtek Bulk-Fill	3.17 (0.03)^{b}	0.52 (0.05)^{b}	1.94 (0.08)^{a,b}	4.63 (0.18)^{e}	2.28 (0.19)^{c}

Identical superscript letters signify that no significant differences were observed among the designated materials within a single column ($p>0.05$). Numbers in parentheses are standard deviations ($n=5$).

Table 4: *Correlations Between the Deflection and the Polymerization Shrinkage, Flexural Modulus, and Polymerization Shrinkage Stress of Composites*

Measured variables	Polymerization shrinkage stress	Deflection					
		1 mm		2 mm		3 mm	
		Bulk	Incremental	Bulk	Incremental	Bulk	Incremental
Polymerization shrinkage	0.393*	0.706**	0.446*	0.282	0.328	0.099	0.17
Flexural modulus	0.033	−0.186	0.048	0.227	0.234	0.376*	0.341
Shrinkage × modulus	0.602**	0.661 **	0.678**	0.71**	0.78**	0.657**	0.727 **
Polymerization shrinkage stress	1	0.832 **	0.969**	0.885**	0.868**	0.785**	0.817 **

*Numbers are Pearson's correlation coefficients (*p<0.05; **p<0.01).*

The six composites used in this study can be classified into three groups according to the level of shrinkage stress they produced: conventional flowable with high stress (Z350F), high viscous bulk-fill (SF and TNB) and conventional (Z250) with moderate stress, and bulk-fill flowable with low stress (SDR and FB). Conventional flowable (Z350F) and bulk-fill flowable (SDR) composites showed the highest and lowest deflections, respectively. On the other hand, both bulk-fill (SF and TNB) and conventional (Z250) composites with moderate stress, which are of high viscosity, exhibited comparable deflections.

Within the composites with moderate stress, the deflection by bulk filling with either TNB or SF was equal to ($p>0.05$) or higher than ($p<0.05$) that by incremental layering with the conventional composite (Z250; Table 2). Therefore, bulk filling of a high viscosity bulk-fill composite with moderate stress does not appear to offer any advantages over incremental layering of a high viscosity conventional composite with moderate stress. Interestingly, TNB always exhibited the lowest deflection among the three composites with moderate stress because of its lowest flexural modulus, even though the three composites exhibited similar polymerization shrinkages.

Unlike the moderate stress groups with high viscosity, bulk filling of bulk-fill flowable composites with low stress (SDR and FB) yielded lower deflections than incremental layering of conventional flowable composites with high stress (Z350F). Despite its low flexural modulus, greater deflection was always observed with FB compared with SDR. This finding may be due to the significantly higher polymerization shrinkage and stress of FB.

The reduction (%) of deflection from bulk to incremental layering was largest for SDR (46.8%), TNB (48.4%), and FB (49.6%) for mold wall thicknesses of 1, 2, and 3 mm, respectively (Figure 6). Thus, bulk-fill composites were more effective in reducing mold wall deflection by incremental layering compared with conventional composites. The reduction of deflection achieved with incremental layering increased as mold wall thickness increased for Z250, Z350F, and FB. Moreover, with the exception of SDR, all composites showed greater reduction of deflection by incremental layering in 3-mm-thick mold wall compared with 1-mm-thick mold wall. In general, reduction of deflection by incremental layering was enhanced in thick mold walls (low compliance; Figure 6). In addition, as the mold wall thickness increased from 1 to 3 mm, the deflection by flowable composites with low modulus decreased more than in high-viscosity composites (Table 2).

The correlation between polymerization shrinkage and mold wall deflection decreased with increasing mold wall thickness. On the other hand, the correlation between flexural modulus and deflection increased with increasing mold wall thickness (Table 4). This result is supported by a previous study of the effect of instrument compliance on polymerization shrinkage stress,[29] which found that shrinkage strain was the major factor in determining stress when instrument compliance was high, whereas shrinkage strain and modulus played equal roles in determining the polymerization shrinkage stress when instrument compliance was restricted. In clinical situations, composites with high shrinkage are likely to produce greater cusp deflection in high compliance cavities, such as a large MOD cavity. In contrast, both the elastic modulus and shrinkage determine the polymerization shrinkage stress in low compliance cavities such as an occlusal cavity.

CONCLUSION

Both conventional and bulk-fill composites showed lower mold wall deflection when incrementally filled. As the mold wall thickness increased, the effect of

incremental layering on the reduction in mold wall deflection was enhanced. In addition, restoration by bulk filling with high viscous bulk-fill composites with moderate stress did not achieve reduction in wall deflection comparable to those obtained with incremental layering with conventional universal composites. When the compliance was high, polymerization shrinkage was the main factor that influenced deflection. In lower compliance cavities, both the flexural modulus and the polymerization shrinkage determined the deflection.

Conflict of Interest

The authors of this manuscript certify that they 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 13 April 2016)

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