치의학박사학위논문

Influence of the cavity wall compliance and layering method on the cusp deflection in bulk-fill composite restoration

Bulk-fill 복합레진 수복 시 와동벽의 compliance와 충전방법이 교두굴곡에 미치는 영향

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Abstract

Influence of the cavity wall compliance and layering method on the cusp deflection in bulk-fill composite restoration

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Objectives. The aim of this study was to investigate the effects of the cavity wall compliance and layering method on the cusp deflection in bulk-fill and conventional composite restorations, and to examine the relationships between the cusp deflection and the polymerization shrinkage, flexural modulus, and polymerization shrinkage stress of composites.

Methods. Six light-cured composites were used in this study. Two of these were conventional methacrylate-based composites (Filtek Z250 [Z250] and Filtek Z350 XT Flowable [Z350F]), whereas four were bulk-fill composites (SonicFill [SF], Tetric N-Ceram Bulk-Fill [TNB], SureFil SDR Flow [SDR], and Filtek Bulk-Fill [FB]). One hundred eighty aluminum molds simulating a Mesio-Occluso-Distal (MOD) cavity (6 [W] × 8 [L] × 4 [D] mm) were prepared and classified into three groups with the 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 (LVDT) probes were used to measure the cusp deflection of each composite ($n = 5$) over a period of 2000 s. Both bulk and incremental filling groups were cured for 80 s totally using Elipar S10 LED light curing unit (1200 mW/cm^2). The polymerization shrinkage, flexural modulus, and polymerization shrinkage stress of the six composites were also measured. Data were analyzed with ANOVA and Tukey's post-hoc tests. Pearson's correlation analysis was conducted to investigate the relationships among variables.

Results. All groups with bulk filling exhibited significantly higher cusp deflection compared with groups with incremental layering ($p < 0.05$). The deflection decreased as mold wall thickness increased. The highest shrinkage stresses were recorded for Z350F (5.07 MPa) and SDR showed the lowest shrinkage stress value (1.70 MPa). The correlation between polymerization shrinkage and the cusp deflection decreased with increasing wall thickness. On the other hand, the correlation between flexural modulus and the cusp deflection increased with increasing wall thickness. For all groups, cusp deflection correlated strongly with polymerization shrinkage stress.

Conclusions. Both conventional and bulk-fill composites showed lower cusp deflection when incrementally filled. Restoration by bulk filling with high viscous bulk-fill composites resulted higher cusp deflection than those obtained by incremental layering of conventional universal composites.

Keywords: Bulk-fill composite, Cavity wall compliance, Cusp deflection, Flexural modulus, Layering method, Polymerization shrinkage strain, Polymerization shrinkage stress

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Contents

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1. 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 c-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. For example, degree of compliance of the instrument can affect the result of measured stress. 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] If the compliance of the teeth is high, that means the teeth will deflect more easily. Several studies have reported that teeth with cavities exhibit relatively high compliance.[9, 14, 15] Thus, to obtain clinically relevant results, cusp compliance should be similar to that observed in clinical situations.

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 MOD cavities (1.5 [W] × 2 [D] and 3 [W] × 2 [D] mm) was 2.96 and 3.32 μm/N, respectively, which is about 3-4 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 cavity wall compliance and layering method on the 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 cavity wall compliance and layering method on the cusp deflection in bulk-fill vs. conventional composite restorations. In addition, the relationships between the cusp deflection and the polymerization shrinkage, flexural modulus, and polymerization shrinkage stress of various composites were also examined.

2. Materials and Methods

2.1. 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, 3M ESPE, St. Paul, MN, USA]) and a flowable (Filtek Z350 XT Flowable [Z350F, 3M ESPE]) composite. The four bulk-fill composites included two high-viscosity composites (SonicFill [SF, Kerr, Orange, CA, USA]/Tetric N-Ceram Bulk-Fill [TNB, Ivoclar Vivadent, Schaan, Liechtenstein]) and two flowable composites (SureFil SDR Flow [SDR, Dentsply, Konstanz, Germany]/Filtek Bulk-Fill [FB, 3M ESPE]). The brand names, types, compositions, and manufacturers of the composites are listed in Table 1. An LED light curing 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.

2.2. Measurement of cusp deflection

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

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 s, the mesially tilted upper side for 20 s, the distally tilted upper side for 20 s, and again the upper surface for 20 s (total 80 s 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 s (total 80 s) 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 ± 1℃) throughout the curing process using two LVDT probes (AX-1, Solartron Metrology, West Sussex, UK), 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 the cusp deflection was initiated 20 s prior to light irradiation to obtain a baseline and continued for up to 2000 s, at a rate of 2 data points/s. The displacements of both sides were added to obtain the total amount of deflection (n = 5).

2.3. 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 disc-shaped composite specimen; this point was set to zero. Baseline data were obtained for 10 s, and then the curing light was turned on for 40 s. The axial shrinkage data were stored on a computer at a rate of 10 data points/s for 600 s (n

= 5). The thickness of the light-cured specimen was measured using a micrometer. The axial polymerization shrinkage (%) was calculated using the following equation:

Axial polymerization shrinkage (%) = 100 × shrinkage / (cured specimen thickness + final shrinkage)

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

2.4. 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 s each (total 200 s). The cured specimens were polished and stored in dry conditions for 24 hours in the dark at room temperature (25 ± 1℃). 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, UK) at a crosshead speed of 0.5 mm/min (supporting span length = 20 mm) (n = 5).

2.5. 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 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), a bonding agent (Scotchbond Multipurpose Adhesive, 3M ESPE), and light cured for 10 s. 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 s and the composite was irradiated with a curing light for 40 s. Measurements were made for each composite, at a rate of 10 data points/s, for 600 s (n=5).

2.6. 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 kg up 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).

2.7. 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 cusp deflection and the polymerization shrinkage, flexural modulus, and polymerization shrinkage stress of the composites. All tests were conducted at $\alpha = 0.05$.

3. Results

3.1. Cusp deflection

The cusp 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 s, 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 (μm) at 2000 s 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 (μm) 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 cusp deflection compared with groups with incremental layering ($p < 0.05$). Cusp deflection decreased with increasing mold wall thickness ($p < 0.05$).

3.2. Axial polymerization shrinkage

The Z350F composite demonstrated the highest polymerization shrinkage (3.52%), followed by Filtek Bulk-Fill (3.17%), SDR (2.88%), Z250 (2.18%), and Tetric N-

Ceram (2.11%), while SonicFill showed the lowest shrinkage (2.08%) (Table 3). No significant differences were observed between Z250, Tetric N-Ceram, and SonicFill 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 SonicFill (0.34 %/s). The time at the peak shrinkage rate (s) was longest (2.11 s) for Z350F and shortest (1.11 s) for Tetric N-Ceram.

3.3. 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 SonicFill, Tetric N-Ceram, Z350F, SDR, and Filtek Bulk-Fill (4.63 GPa). With the exception of Z350F and SDR ($p = 0.888$), the composites exhibited significantly different flexural modulus values ($p < 0.05$).

3.4. Polymerization shrinkage stress

The highest shrinkage stresses were recorded for Z350F (5.07 MPa) and SDR showed the lowest shrinkage stress value (1.70 MPa) (Table 3). No significant differences were observed between Z250, Tetric N-Ceram, and SonicFill ($p > 0.05$).

3.5. 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.

3.6. 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 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).

4. 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 deflection 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 (SureFil SDR Flow and Filtek Bulk-Fill Flowable) 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 (SonicFill and Tetric N-Ceram Bulk-Fill) 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, Filtek Bulk-Fill) were higher than those of high-viscosity composites (Z250, SonicFill, Tetric N-Ceram). 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 Filtek Bulk-Fill) 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 bulk-fill flowable composite contains the patented, modified UDMA 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, Filtek Bulk-Fill 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, Filtek Bulk-Fill) exhibited lower polymerization shrinkage stress compared with the high-viscosity bulk-fill composites (SonicFill, Tetric N-Ceram). 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 manufacturer's information are as follows: SonicFill (83.5 wt%/69 vol%), Tetric N-Ceram (79-81 wt%/-), SDR (68.0 wt%/45 vol%), and Filtek Bulk-Fill (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, 4 definite reductions in deflection due to thermal expansion effects could be clearly observed.[4]

Cusp deflection decreased as mold 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 cusp 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] They 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.

The six composites used in this study can be classified into 3 groups according to the level of shrinkage stress they produced: conventional flowable with high stress (Z350F), high viscous bulk-fill (SonicFill, Tetric N-Ceram) and conventional (Z250) with moderate stress, and bulk-fill flowable with low stress (SDR, Filtek Bulk-Fill). Conventional flowable (Z350F) and bulk-fill flowable (SDR) composites showed the highest and lowest deflections, respectively. On the other hand, both bulk-fill (SonicFill, Tetric N-Ceram) 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 Tetric N-Ceram or SonicFill 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, Tetric N-

Ceram 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, Filtek Bulk-Fill) 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 Filtek Bulk-Fill compared with SDR. This finding may be due to the significantly higher polymerization shrinkage and stress of Filtek Bulk-Fill.

The reduction (%) of deflection from bulk to incremental layering was largest for SDR (46.8%), Tetric N-Ceram (48.4%), and Filtek Bulk-Fill (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 Filtek Bulk-Fill. 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 mm 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 cusp 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.

5. Conclusions

Both conventional and bulk-fill composites showed lower cusp deflection when incrementally filled. As the mold wall thickness increased, the effect of incremental layering on the reduction in cusp deflection was enhanced. Restoration by bulk filling with high viscous bulk-fill composites resulted higher cusp deflection than those obtained by incremental layering of conventional universal composites. When the compliance was high, polymerization shrinkage was the main factor that influenced cusp deflection. On the contrary, in cavities with lower compliance, both the flexural modulus and the polymerization shrinkage determined the cusp deflection.

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Tables and Figures

Table 1. Brand name, type, composition, and manufacturer of each composite used in this study

Composite (Code, Shade, lot No.)	Type	Composition	Manufacturer
Filtek Z250 (Z250, A2, N482264)	C, H	Bis-GMA, Bis-EMA, TEGDMA, UDMA 0.01-3.5 μmZr/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 ytterbium trifluoride, Ba-glass filler, 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 μmnano-clusters (65 wt%/-)	3M ESPE, St. Paul, MN, USA
SureFil SDR Flow (SDR,Universal,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: C, conventional composite; B, bulk-fill; H, high-viscosity; F, flowable. *, Bulk-fill composites requiring a 2-mm capping layer as recommended by manufacturers. Bis-EMA, bisphenol-A polyethylene glycol dietherdimethacrylate; Bis-GMA, bisphenol-A diglycidyl ether dimethacrylate; EBPDMA, ethoxylated bisphenol-A-dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

Table 2. Mean cusp deflection (µm) for each group at 2000 s

Composite	Layering Method	Aluminum Mold Wall Thickness		
		1 mm	2 mm	3 mm
Filtek Z250	Bulk	35.6 (1.2) [B,a]	19.0 (0.6) [B,c]	13.4 (2.0) [B,d]
	Incre-mental	28.4 (0.9) [CD,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]
	Incre-mental	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]
	Incre-mental	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]
	Incre-mental	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) [CD,a]	10.8 (1.1) [D,c]	4.8 (0.2) [D,e]
	Incre-mental	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]
	Incre-mental	23.4 (0.8) [E,b]	8.9 (0.7) [DE,d]	4.8 (0.8) [D,e]

Identical upper case letters: No significant difference among groups of the same wall thickness ($p > 0.05$).

Identical lower case letters: No significant difference among groups of the same composite ($p > 0.05$).

Numbers in parentheses are standard deviations ($n = 5$).

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 (%)	Max. 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) [abc]	7.97 (0.44) [b]	2.73 (0.10) [b]
Tetric N-Ceram Bulk-Fill	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 Flow	2.88 (0.13) [c]	0.64 (0.01) [a]	1.67 (0.08) [bc]	5.62 (0.20) [d]	1.70 (0.16) [d]
Filtek Bulk-Fill Flowable	3.17 (0.03) [b]	0.52 (0.05) [b]	1.94 (0.08) [ab]	4.63 (0.18) [e]	2.28 (0.19) [c]

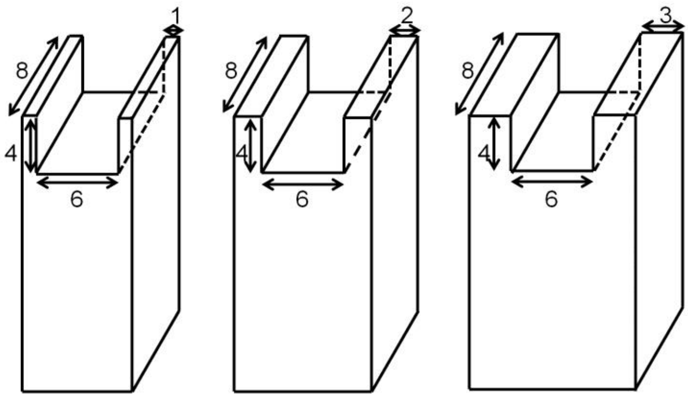
Identical superscript letters signify that no significant differences were observed among the designated materials within a single column ($p > 0.05$).

Numbers in parentheses are standard deviations ($n = 5$).

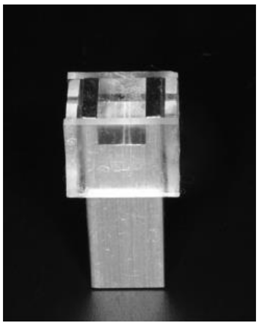
Table 4. Correlations between the cusp deflection and the polymerization shrinkage, flexural modulus, and polymerization shrinkage stress of composites

	Polymerization Shrinkage Stress	Cusp Deflection					
		1 mm		2 mm		3 mm	
		Bulk	Incre-mental	Bulk	Incre-mental	Bulk	Incre-mental
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 **

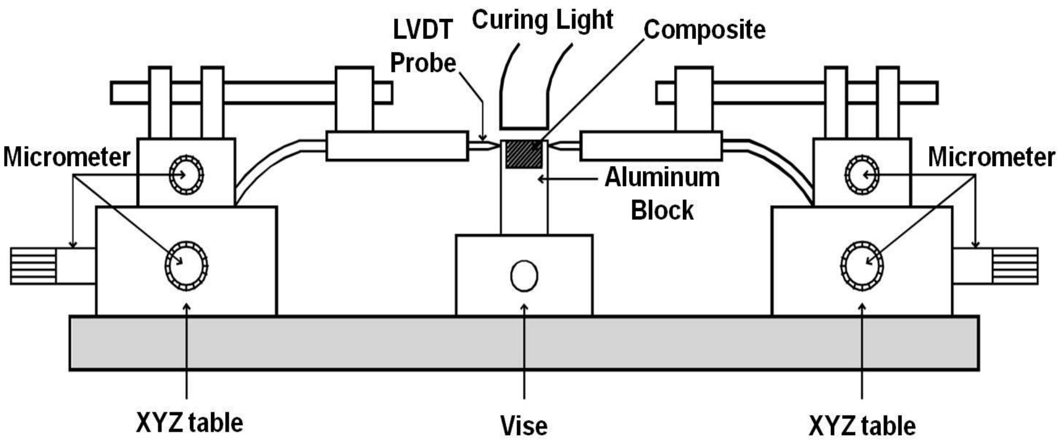
Numbers are Pearson's correlation coefficients (** $p < 0.01$, * $p < 0.05$).


1
2
3
8
8
8
4
4
4
6
6
6

(a)

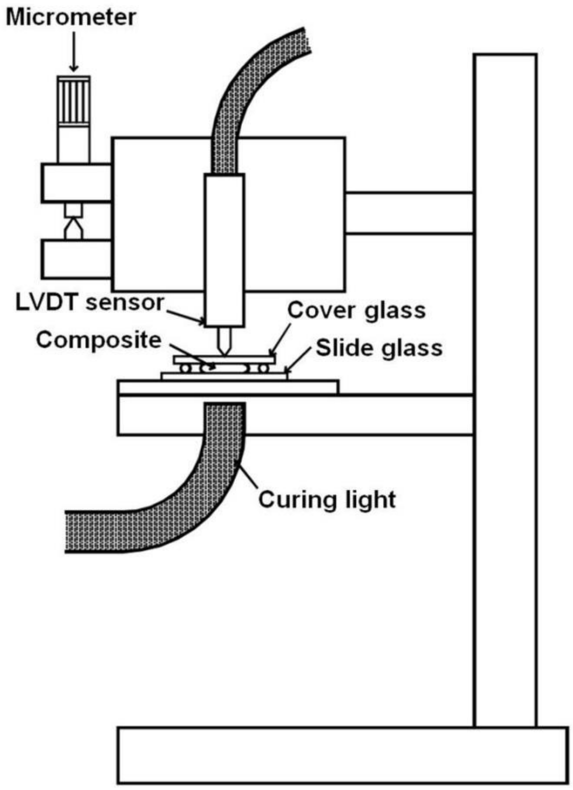


(b)

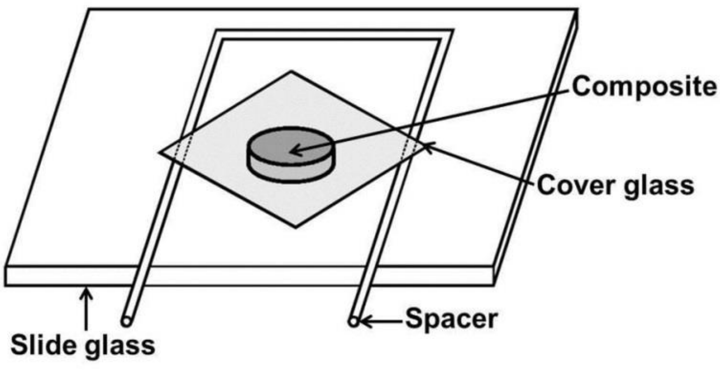

LVDT
Probe
Curing Light
Composite
Micrometer
Micrometer
Aluminum
Block
XYZ table
Vise
XYZ table

(c)

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 the cusp deflection.


Micrometer
LVDT sensor
Cover glass
Composite
Slide glass
Curing light

(a)


Composite
Cover glass
Slide glass
Spacer

(b)

Figure 2. (a) Instrument for measuring polymerization shrinkage using the modified bonded disc method. (b) Specimen preparation.

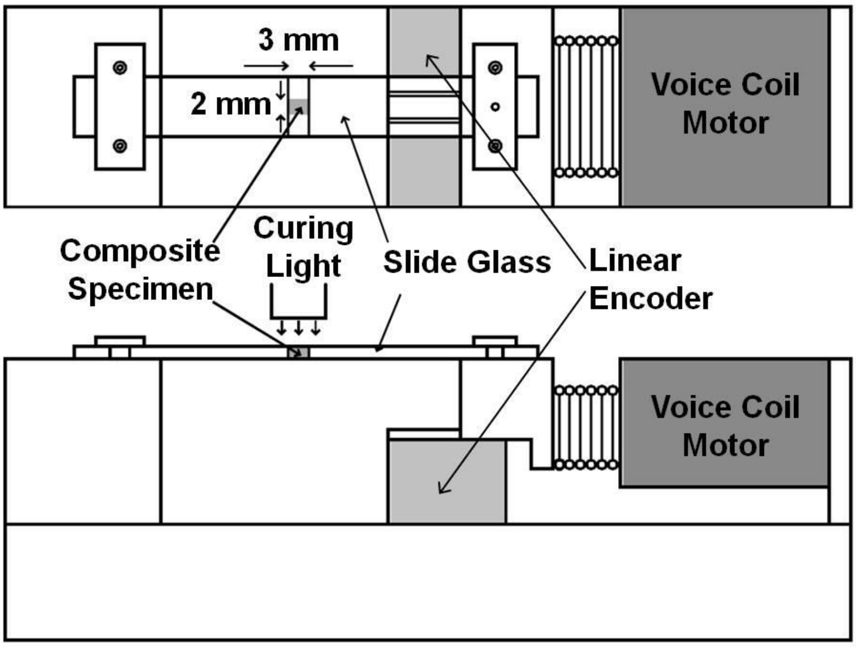


Figure 3. Instrument for measuring polymerization shrinkage stress using a voice coil motor with feedback mechanism.

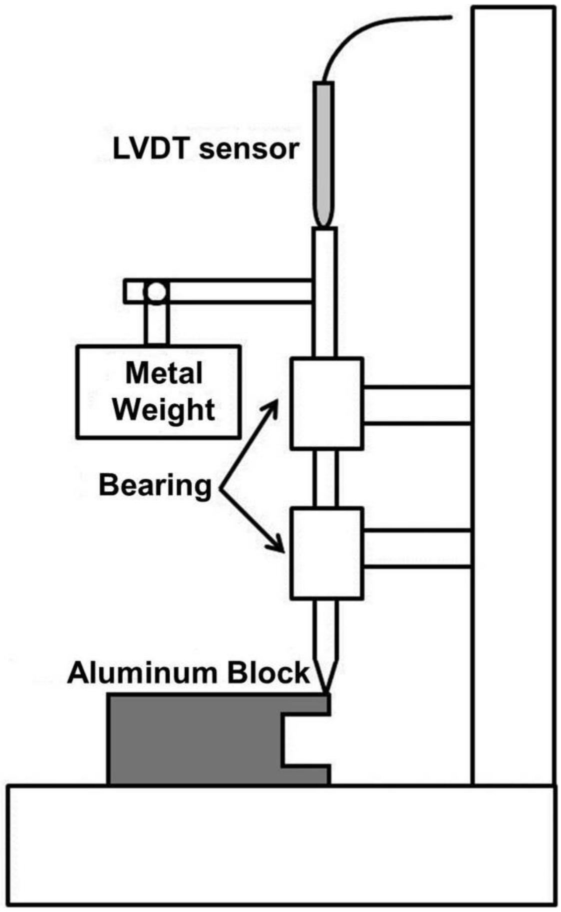


Figure 4. Instrument for measuring the compliance of the aluminum blocks.

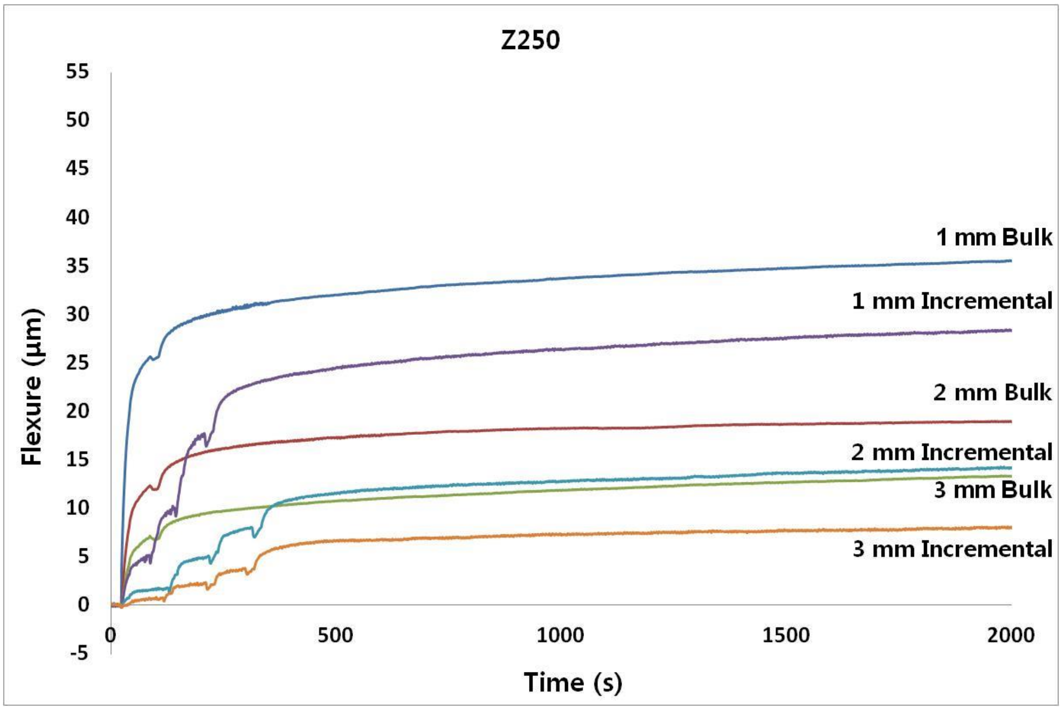


Figure 5. The cusp deflection (µm) of the Z250 composite with varying mold wall thicknesses and layering methods as a function of time.

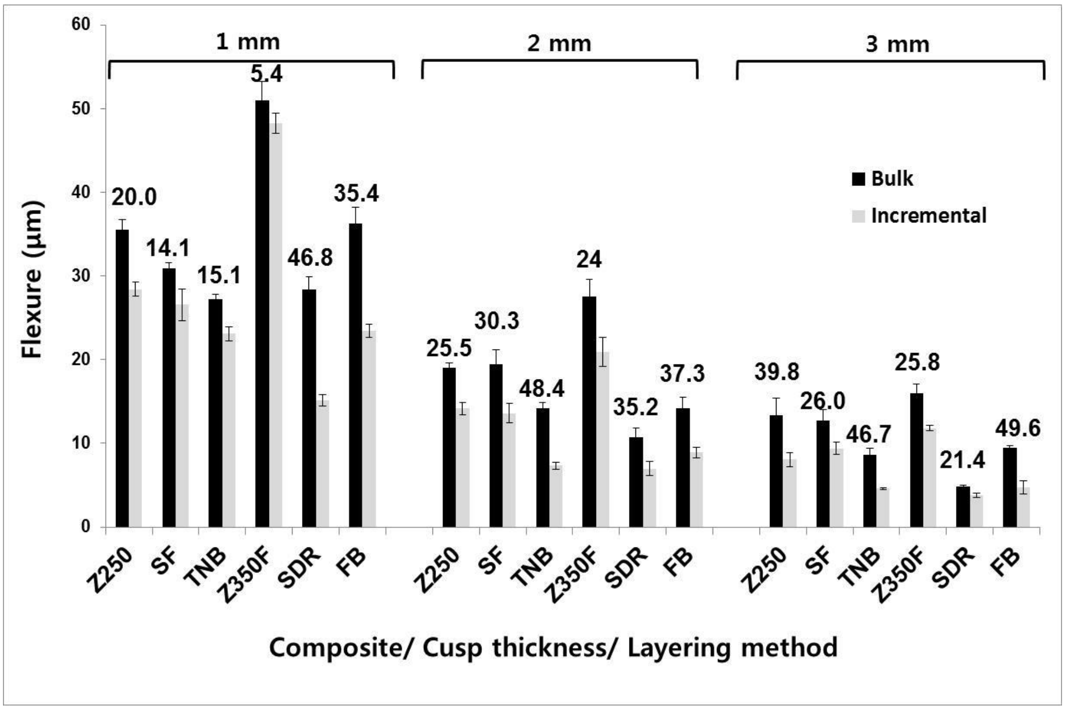


Figure 6. Mean cusp deflection (μm) and reduction in deflection from bulk to incremental layering (%) for each composite according to mold wall thickness and layering method. The number above each bar indicates the reduction (%) in deflection from bulk to incremental layering.

국문초록

Bulk-fill 복합레진 수복 시 와동벽의 compliance와 충전방법이 교두굴곡에 미치는 영향

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1. 목적

본 연구에서는 bulk-fill과 conventional 복합레진 수복 시 와동벽의 compliance와 충전방법이 교두굴곡에 미치는 영향을 알아보고, 교두굴곡과 복합레진의 중합수축, 탄성계수, 중합수축응력과의 연관성을 고찰하였다.

2. 재료 및 방법

6 종의 광중합 복합레진을 사용하였다. 2 종은 conventional methacrylate 기반 복합레진이며 (Filtek Z250 [Z250]과 Filtek Z350 XT Flowable [Z350F]), 4 종은 bulk-fill 복합레진 (SonicFill [SF], Tetric N-Ceram Bulk-Fill [TNB], SureFil SDR Flow [SDR], Filtek Bulk-Fill [FB])이다. 근심-교합-원심 (MOD) 와동을 (6 [협설] × 8 [근원심] × 4 [깊이] mm) 모방한 180 개의 알루미늄 몰드를 준비하여 와동벽의 두께 1, 2, 3 mm에 따라 3 그룹으로 분류하였다. 각 그룹은 복합레진의 충전 방법 (bulk 또는 incremental)에 따라 다시 2 그룹으로 세분하였다. 2 개의 LVDT (linear variable differential transformer) probe를 이용하여 2000 초 동안 각 소그룹의 와동벽의 굴곡을 실시간으로 측정하였다 (n = 5). Bulk 또는 incremental 그룹 모두 Elipar S10 LED 광중합기 (1200 mW/cm^2)를 이용하여 총 80 초 광중합 하였다. 또한 6 종 복합레진의 중합수축, 탄성계수, 중합수축 응력을 측정하였다. 분산분석 (ANOVA) 및 Tukey 사후검정으로 통계분석을 시행하고, 피어슨 상관 관계 분석 (Pearson's correlation analysis)으로 변수들 간의 관계를 알아보았다.

3. 결과

Bulk filling한 모든 그룹은 incremental layering한 그룹보다 통계적으로 유의하게 큰 교두굴곡을 나타내었다 ($p < 0.05$). 와동벽의 두께가

증가할수록 교두굴곡은 감소하였다. 가장 큰 중합수축응력은 Z350F (5.07 MPa)가 나타내었고, SDR이 가장 작은 중합수축응력 (1.70 MPa)을 보였다. 와동벽의 두께가 증가할수록, 중합수축과 교두굴곡 사이의 상관성이 감소하였다. 반면, 탄성계수와 교두굴곡의 상관성은 와동벽이 두꺼워짐에 따라 증가하였다. 모든 그룹에서 교두굴곡은 중합수축응력과 강한 상관관계를 나타내었다.

4. 결론

Conventional과 bulk-fill 복합레진 모두 incremental layering 하는 경우 더 적은 교두굴곡을 나타내었다. 고점도 bulk-fill 복합레진을 bulk filling하는 것이 conventional universal 복합레진을 incremental layering하는 것보다, 더 큰 교두굴곡을 나타내었다.

주요어: Bulk-fill 복합레진, 와동벽의 compliance, 교두굴곡, 탄성계수, 충전방법, 중합수축, 중합수축응력

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