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Research article

Comparison of the stress distribution in base materials and thicknesses in composite resin restorations

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ABSTRACT

Resin-based composite materials are commonly used for restorations, but their dimensional changes during the polymerization could cause various clinical problems. This study evaluated the influence of a base of different materials and thicknesses on the stress magnitude and distribution in a second maxillary premolar with an MOD resin composite restoration using three-dimensional finite element analysis. A sound tooth without cavity was considered as the control group (ST), and another group was restored with composite resin without applying a base material in a MOD cavity (CR). The other three groups were restored with composite resin along with the following base materials: glass ionomer cement, low-viscosity resin, and tricalcium silicate, respectively (CR-GIC, CR-LR, and CR-TS). These three groups were further divided into two subgroups according to the thickness of the base layer: thin (0.5 mm) and thick (1.0 mm). The stress distribution was compared using the maximum principal stress after polymerization shrinkage and vertical loading with 600 N on the occlusal surface. Group ST showed the lowest stress value, and its stress propagation was confined to outer enamel surfaces only. Group CR demonstrated the highest stress distribution in the tooth-restoration interface with increased failure risk on marginal areas. The thin and thick subgroups of the three groups with a base layer had lower stress levels than Group CR. The base materials reduced the marginal stress caused by polymerization shrinkage of composite resin in MOD cavities. Different base materials and thicknesses did not affect the stress distribution.

1. Introduction

Resin-based dental composite materials are commonly used for class I and class II adhesive restorations due to their esthetic and

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physical properties, as well as their availability [1,2]. Despite the advantages of these materials, there has been a major concern that dimensional changes during the polymerization process could cause stress within the material and its interface with the tooth structure, as the resin composite bonds to tooth structures through micromechanical interlocking [3]. The biomechanical behavior and the life span of maxillary premolars are heavily influenced by the loss of coronal tooth structure, especially the marginal ridges, which are structurally very important [4]. Class II mesio-occlusal-distal (MOD) cavities, which result in the loss of both marginal ridges, significantly weaken the teeth. When a MOD cavity is restored with direct composite resin, the internal stress generated by polymerization shrinkage may be transferred to the bonded tooth, leading to enamel cracks, cuspal deflection, and deformation of tooth walls [5–7].

In order to minimize the negative effects of polymerization shrinkage in the clinical setting, the sandwich technique has been suggested [8]. This method involves placing an intermediate base or liner underneath the resin-based composite on the cavity floor. The underlying base or liner material may act as a stress-absorbing layer, reducing internal stress from shrinkage by replacing the volume of resin composite mass [9]. Different types of base materials can be used in the sandwich technique, and these materials are normally indicated by its lower shrinkage rate and enough strength to withstand the forces of occlusion [10,11]. Glass ionomer cement (GIC) is well-known for its biocompatibility and chemical adhesion ability without shrinkage during setting [10]. The use of resin-based materials with lower elastic moduli and lower viscosity, such as flowable resins, has also been suggested because these materials increase the strain capacity and reduce the stress on the adhesive interface [12,13]. Tricalcium silicate based cement has gained popularity in recent years for its high fracture strength, chemical stability and biocompatibility [14]. Tricalcium silicate based cement was recommended as an alternative choice for the base material under posterior direct resin restorations [15].

Choosing the base material requires careful consideration to minimize the unfavorable effects of polymerization shrinkage of resin composites. Although many choices are available for base materials to use with direct resin restorations, there is no consensus regarding the most appropriate base material and thickness. Although it has been suggested that base materials with lower elastic moduli relieve polymerization shrinkage effects due to their ability to stretch [16], *in vitro* studies have shown inconsistent results regarding the effects of different elastic moduli of base materials [11,17,18]. Moreover, there is a lack of scientific evidence on the influence of different thicknesses of the base material on polymerization shrinkage stress [19]. A biomechanical investigation is needed to analyze and compare the influence of different base materials and thicknesses on the polymerization shrinkage effects of composite resin in order to suggest an ideal material and thickness for clinical practice.

Three-dimensional finite element analysis (3D FEA) has emerged as an effective tool to investigate biomechanical behavior; in particular, it has been utilized to evaluate the stress distribution in teeth and dental materials [20]. Several studies using FEA have analyzed the residual stress caused by polymerization shrinkage of direct resin restorations [21–23]. Previous FEA studies have also investigated the influence of different base materials in direct composite resin restorations under functional loading [24–26]. However, none of those FEA studies considered the effects of different base thicknesses and base materials with high elastic moduli, such as tricalcium silicate cement.

The aim of this study was to investigate the influence of the application of a base of different materials and thicknesses on the stress magnitude and distribution in a second maxillary premolar with an MOD resin composite restoration using a 3D FEA.

2. Materials and methods

This study utilized a 3D model of the upper left second premolar, derived from the maxillary cone-beam computed tomographic (CBCT) image referenced in a previous study [27]. The CBCT image of a healthy Korean male adult was cut into 0.25 mm thicknesses to obtain two-dimensional images. These images were used to reconstruct a three-dimensional maxilla model using 3D slicer (open-source software, https://www.slicer.org). A single-tooth model was constructed by extracting the part of the model that corresponded to the upper left second premolar region. The external contours of the tooth model, as well as the internal enamel and dentin contours,

Table 1
Total number of elements and nodes of all finite element analysis models.

Group	Material	Number of nodes	Number of elements
SR	Enamel	370,671	66,276
	Dentine	434,377	83,179
CR	Enamel	230,414	46,489
	Dentine	744,944	136,448
	Adhesive layer	176,357	49,074
	Composite Resin	613,401	116,798
CR-GIC, CR-LR, CR-TS (with thin base layer)	Enamel	233,840	47,087
	Dentine	629,214	115,408
	Adhesive layer	169,795	48,765
	Base	199,500	39,136
	Composite Resin	483,305	92,177
CR-GIC, CR-LR, CR-TS (with thick base layer)	Enamel	230,412	117,394
	Dentine	754,577	137,992
	Adhesive layer	196,816	54,229
	Base	305,127	57,360
	Composite Resin	502,298	95,867

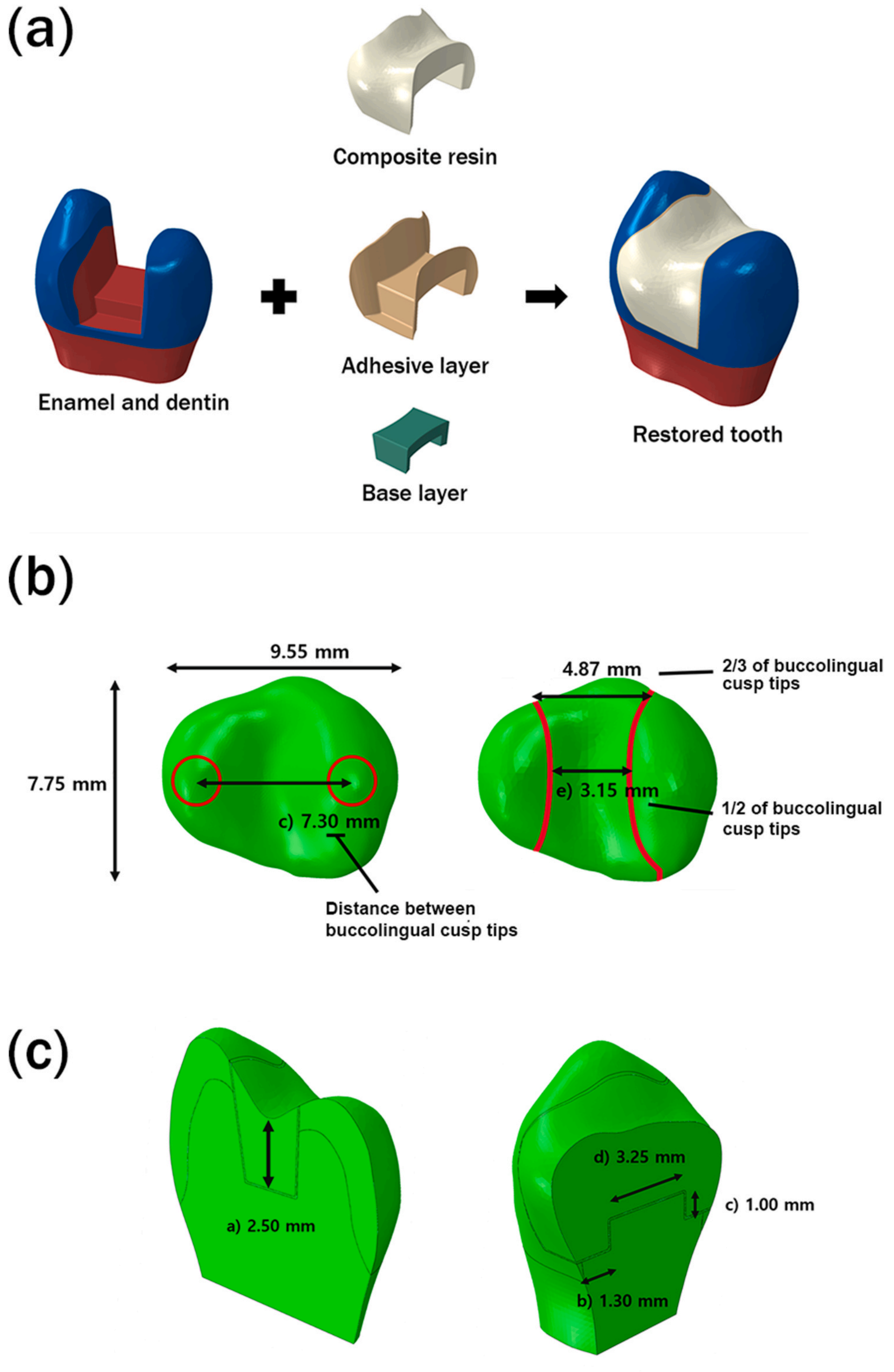

Fig. 1. Illustration of the study model design. (a) dentin and enamel, (b) composite resin, (c) adhesive layer, (d) intermediate base, and (e) restored tooth.

were outlined using ANSYS SpaceClaim 2021 (ANSYS Inc., Canonsburg, PA, USA).

The three-dimensional models were reconstructed in meshes using ANSYS Mechanical 2021 R2 (ANSYS Inc., Canonsburg, PA, USA), and the total number of elements and nodes of all FEA models that were fabricated are listed in Table 1.

The designs of the inlay preparation of the tooth, bonding layers, and base materials were constructed via derived tools from ANSYS SpaceClaim 2021, as are illustrated in Fig. 1a.

The bucco-lingual dimension of the tooth model was 9.55 mm, and its mesio-distal dimension was 7.75 mm. The distance between the buccal and lingual cusp tips of the sound tooth model was measured as 7.30 mm, and its middle point was set as the center line of the inlay preparation design. The width of the inlay preparation was considered as half of the measured distance between the buccal and lingual cusp tip, corresponding to 3.15 mm. The width of the mesial and distal proximal boxes was set as 4.87 mm, which was two-thirds of the distance between the buccal and lingual cusp tips (Fig. 1b). The height of the axial wall was set as 1.00 mm, and the pulpal floor was 2.50 mm below the central fossa. The width of the gingival floor was set as 1.30 mm. A 95° cavity-margin-angles with a rounded bevel on the axio-pulpal line angles was considered in the preparation design (Fig. 1c).

The resin composite models were constructed according to the tooth preparation design. The base materials were designed to cover the pulpal floor and axial walls of the prepared tooth. The base materials in the present study have two different designs according to their thickness (Fig. 2), which was 0.5 mm or 1.0 mm. Both base designs had the same gingival width (0.5 mm), and only differed in pulpal height by 0.5 mm.

The constructed 3D models of tooth and materials were imported into ANSYS Mechanical 2021 R2 (ANSYS Inc., Canonsburg, PA, USA). A sound tooth without cavity was considered as the control group, and another group was restored with composite resin without applying a base material in a MOD cavity. The other three groups were restored with composite resin and a base material: with glass ionomer cement, low-viscosity resin and tricalcium silicate, respectively.

Group ST: Sound tooth.

Group CR: Composite resin without base material.

Group CR-GIC: Composite resin with glass ionomer cement base.

Group CR-LR: Composite resin with low-viscosity resin base.

Group CR-TS: Composite resin with tricalcium silicate cement base.

Group CR-GIC, CR-LR, and CR-TS had a multilayer construction consisting of an adhesive layer, base, and composite resin. The base materials were designed to cover the prepared tooth's pulpal floor and axial walls. These groups were further divided into two sub-groups according to the thickness of the base layer: thin (0.5 mm, tn, Fig. 2a) and thick (1.0 mm, tk, Fig. 2b). Both base designs had the same gingival width (0.5 mm) and only differed in pulpal height by 0.5 mm.

All groups with composite resin restoration included a 0.007 mm thick adhesive layer underneath the composite resin. The experimental design was created and analyzed to investigate the influence of different base materials and thicknesses on stress distribution.

Different values of the Young's modulus and Poisson's ratio of the tooth structure and other restorative materials were assumed. The data used in the study were based on previous studies [24,28,29] and are summarized in Table 2. The maximum principal stress criterion was used when analyzing the results.

The combined effects of the polymerization shrinkage of resin-based materials and occlusal loading was analyzed in terms of stress distribution. The polymerization shrinkage effect was processed in prior to occlusal load.

The thermal expansion approach was used to simulate the effect of polymerization shrinkage affecting the resin composite materials and adhesive layers, assuming a linear thermal expansion coefficient of 0.01. Therefore, contraction stress was generated at the tooth-restoration interface by simulating 1 °C drop in the temperature of the resin-based materials. The assigned magnitude of linear shrinkage was 1.0 %.

A food bolus model was fabricated to simulate occlusal force. The food bolus had an occluding surface that opposed the occlusal surface of the tooth model. The contact area between the food bolus and tooth was confined to the central area between the bucco-

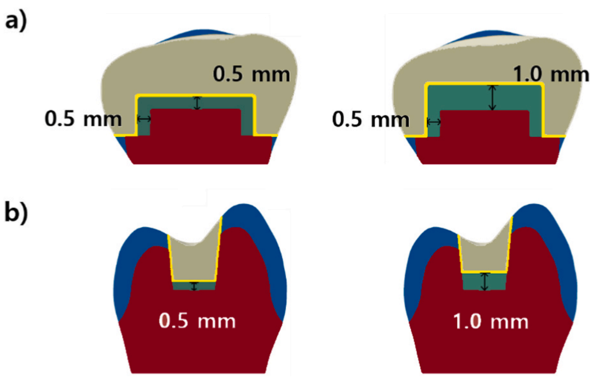

Fig. 2. Model design of the thin (left) and thick (right) base material. (a) mesio-distal cross-sectional view, and (b) bucco-lingual cross-sectional view.

Table 2
Data on mechanical properties used in the study.

Type	Material	Young's modulus (GPa)	Poisson's ratio	Linear thermal expansion coefficient	Reference
Tooth structure	Dentin	18	0.23	–	[26]
	Enamel	80	0.3	–	[26]
Food bolus	Food Bolus	3.4	0.1	–	[29]
Resin materials	Direct Composite Resin	12	0.25	0.01	[26]
	Adhesive Layer	4	0.3	0.01	[26]
Base materials	Glass Ionomer Cement	8	0.25	–	[26]
	Low viscosity Resin	6	0.3	0.01	[26]
	Tricalcium Silicate Cement	22	0.3	–	[27]

lingual cusp tips and the mesio-distal ridges. A 600 N static vertical force, simulating the maximum bite force [30], was loaded on the occlusal surface of the tooth through the food bolus model to simulate the closing phase of mastication (Fig. 3). Displacements were fixed in all directions at the bottom horizontal plane of the tooth structure.

As a linear static analysis was used, all the materials were assumed to behave as elastic materials throughout the entire deformation process, with isotropic characteristics and homogeneity in all directions.

3. Results

The stress distribution of all groups after simulating the concurrent impacts of polymerization shrinkage and occlusal loading of 600 N is displayed in Figs. 4 and 5. Overall, the stress pattern was mainly affected by the shrinkage effects of the composite resin than by the effect of occlusal loading of 600 N.

In the sound tooth model (ST), the stress was uniformly distributed; the enamel showed the lowest maximum principal stress value, and no critical stress concentration was observed (Fig. 4a). The stress-absorbing effect of dentin was displayed in the bucco-lingual cut section (Fig. 5a).

Group CR (composite resin without a base layer) demonstrated a highly concentrated stress distribution on both the restoration and tooth, along the marginal interface, especially at the marginal angles (Fig. 4b). Internal stress was observed within the composite resin material, originating from all marginal inter-surfaces (Fig. 5b).

In base layer applied groups (CR-GIC, CR-LR, and CR-TS), a moderate level of stress on the surface of composite resin was observed, and the stress was intensified near the marginal interfaces (Fig. 4c–h). A low range of stress was transferred to the enamel region on marginal angles. In the bucco-lingual sectional view, localized stress concentrations along the marginal interfaces within the composite resin were displayed. Group CR-LR (both of with and without base layer) showed a moderate level of internal stress within the low-viscosity resin base (Fig. 5e and f).

In the comparison of Group CR-GIC, CR-LR, and CR-TS, no notable difference was observed in the stress pattern and magnitude on both the tooth structure and composite resin (Fig. 5c–h). The thin and thick base groups (tn and tk) also showed no differences in the stress distribution on both the tooth and composite resin.

The highest maximum principal stress values of each tooth-restoration interface in all groups (Fig. 6a) under combined loading conditions were compared in the graph (Fig. 6b). Group CR showed the highest stress value on all surfaces. Similar stress magnitudes were noted between the base layer applied groups, regardless of the thickness.

4. Discussion

This study investigated the effects of different base materials and thicknesses under class II MOD direct resin restorations in terms of the stress distribution. Since the tooth structure exhibits brittle behavior, the maximum principal stress criterion was used to assess the damage resulting from functional loads applied to the tooth [31].

The composite resin restoration without a base material (CR) showed critical concentrations of stress along the marginal surfaces on both the enamel and composite resin. The concentration of stress on the marginal area was caused by internal contraction forces on the resin-tooth interface generated by volumetric changes of the resin composite material. The present result verifies the findings of

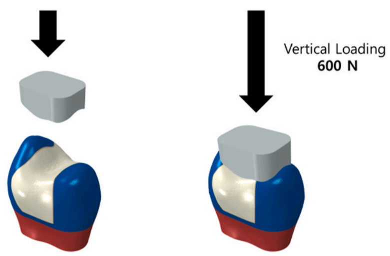

Fig. 3. Illustration of the tooth and food bolus: simulation of 600 N occlusal loading.

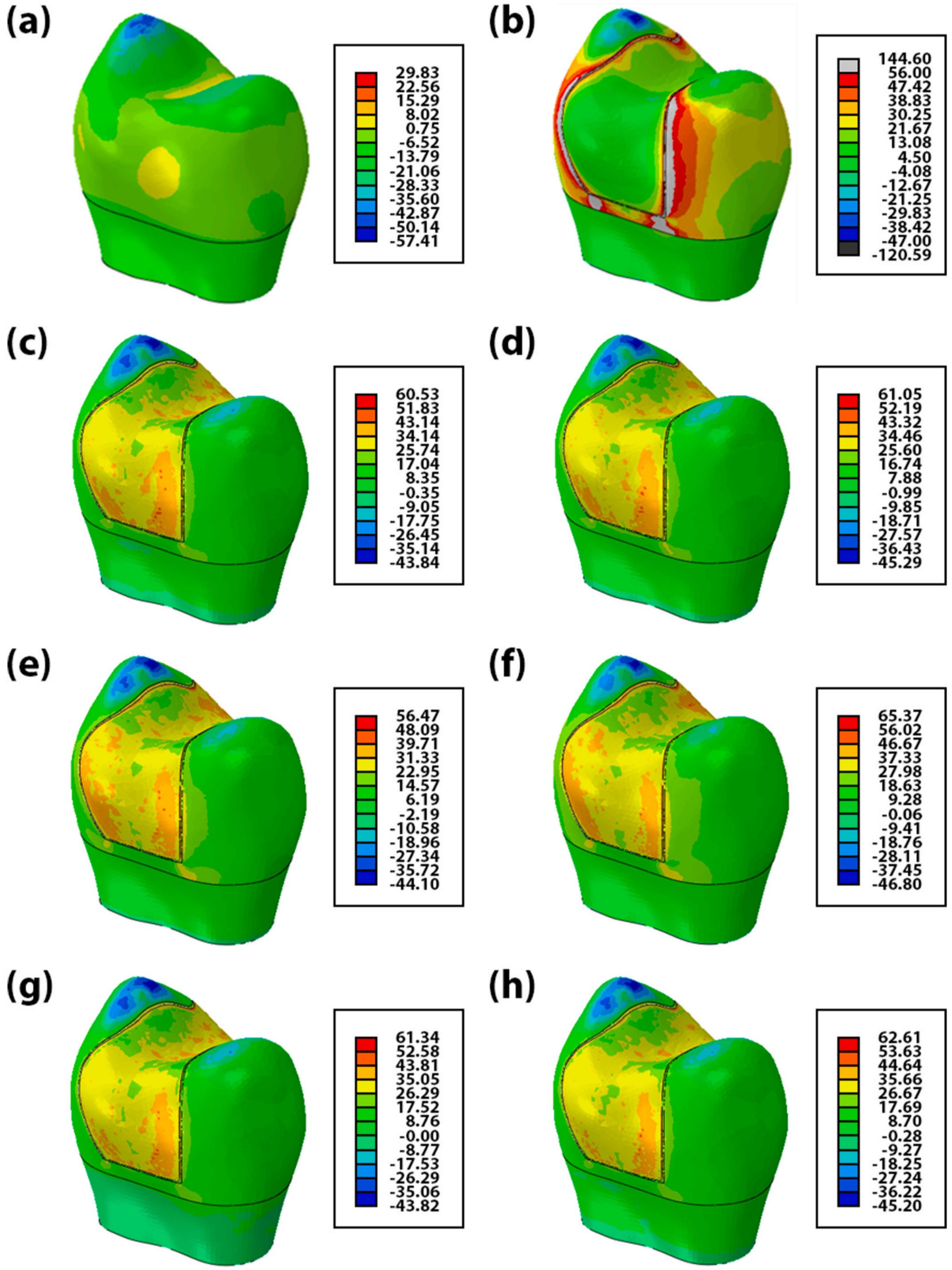

Fig. 4. Stress distribution after the shrinkage effect and 600 N vertical loading in the outer view. (a) ST, (b) CR, (c) CR-GIC-tn, (d) CR-GIC-tk, (e) CR-LR-tn, (f) CR-LR-tk, (g) CR-TS-tn, and (h) CR- TS-tk.

previous studies that polymerization shrinkage may lead to marginal failure via dimensional changes and contraction stress [3,7]. On the other hand, the application of a base material such as GIC, low-viscosity resin, and tricalcium silicate cement under composite resin restorations reduced stress on the tooth-restoration interface compared to direct composite resin without a base layer. This finding is supported by previous laboratory study [10], which suggested that the presence of a base material in direct resin restoration helps to reduce the stress caused by the polymerization shrinkage effect of composite resin. The reduction in the volume of composite resin and

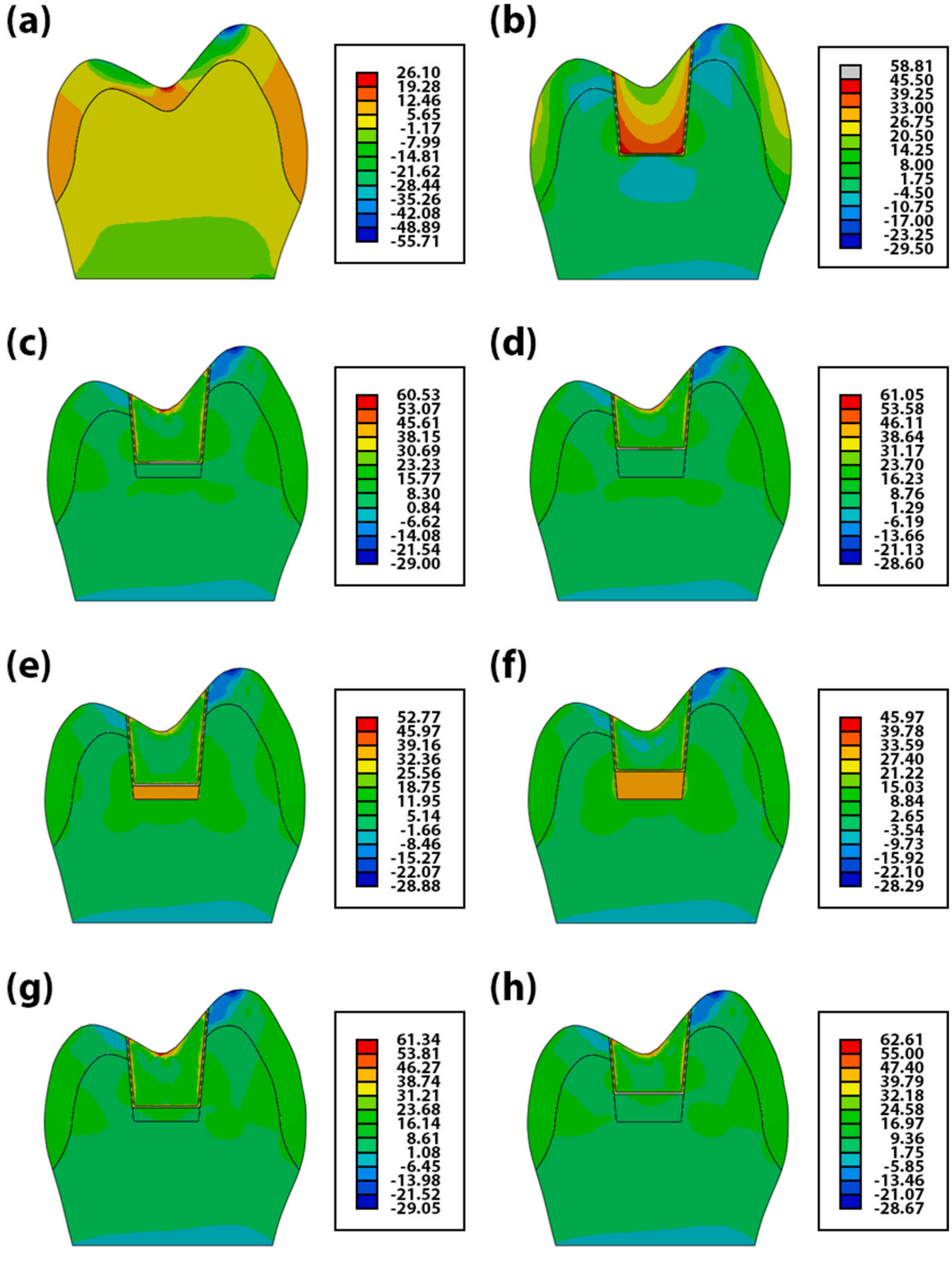

Fig. 5. Stress distribution after the shrinkage effect and 600 N vertical loading in the bucco-lingual cross-sectional view. (a) ST, (b) CR, (c) CR-GIC-tn, (d) CR-GIC-tk, (e) CR-LR-tn, (f) CR-LR-tk, (g) CR-TS-tn, and (h) CR- TS-tk.

bonded surface area may have reduced the unfavorable impacts of polymerization shrinkage, as the shrinkage stress of resin material is affected by its configuration factor and volume [21,23].

In the results of this experiment, the type of base material did not make a difference in stress distribution between tooth and composite resin. Previous studies [17,19] suggested that base materials with low elastic moduli may relieve the stress caused by polymerization shrinkage of composite resin due to their ability to stretch, allowing relaxation of the contraction force. However, the different elastic moduli of the base materials in the present study did not affect the stress pattern and magnitude of polymerization

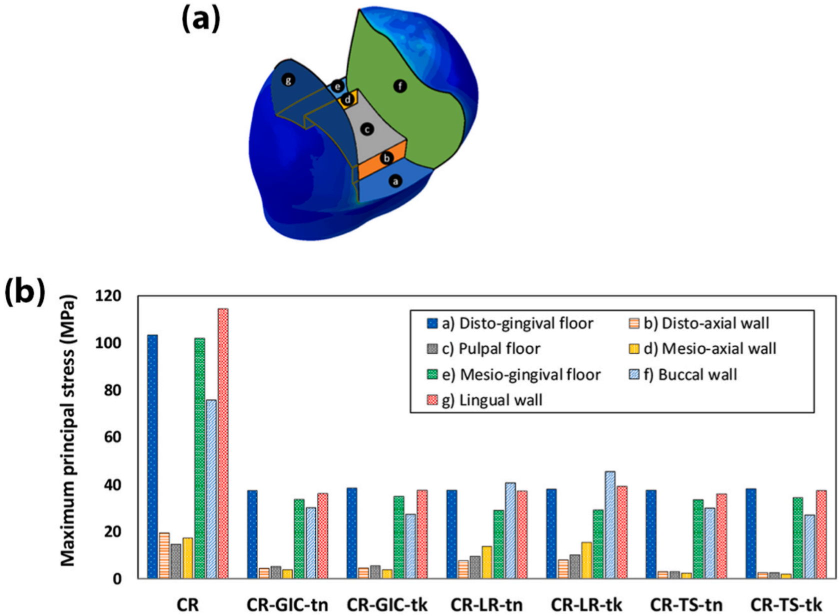

Fig. 6. (A) Labels of each tooth-restoration interface, (b) Comparison in Maximum principal stresses (MPa) on each surface.

shrinkage of the composite resin. It seems that the influence of different elastic moduli of the base materials may have been masked by the predominant effect of the configuration factor and volumetric dimensional changes of the composite resin material [24].

Although Group CR-LR showed a moderate range of internal stress within the base layer due to the shrinkage effect, the stress pattern and magnitude of the composite resin were not different from those of other base layer applied groups (CR-GIC and CR-TS), which are non-shrinking base materials. A previous study [32] explained that flowable resin with elastic moduli of 5 MPa or higher did not efficiently act as stress-relieving layers. The elastic moduli of the base materials used in the present study were more than 5 MPa. Furthermore, the thickness of the layer in the above-mentioned study [32] was thicker (1.4 mm) than in our study (0.5 and 1.0 mm). It seems that the stress-relieving effect of the resin base layer was not sufficiently impactful in terms of the elastic moduli of base material and thickness in the present experimental design. This result is in accordance with a previous 3D FEA study [24], which showed that neither non-shrinking GIC nor shrinking flowable resin base materials significantly modified the stress patterns caused by polymerization shrinkage of the composite resin. It seems that the low level of stress caused by the shrinkage of the low-viscosity resin base was covered by the shrinkage effect of the composite resin, since the configuration factor and volumetric shrinkage of the low-viscosity resin were less relevant than for composite resin. These results are consistent with the previous FEA study [18] and *in vitro* experimental studies [31,33].

Likewise, no influence of different thicknesses of base layer was observed in the present study. The base thickness design used herein only involved a 0.5 mm difference in pulpal height with a fixed gingival width. This was insufficient to yield a meaningful difference according to the thickness of the base layer. Analogously, a previous *in vitro* study showed that a difference in the layer thickness between 0.5 mm and 1.0 mm in both resin-modified GIC and low-viscosity resin bases led to no differences in the polymerization contraction forces caused by composite resin [19].

This study had several limitations. In this study, only a static axial load of 600 N was applied. However, many factors affect bite force such as sex, age, restorations, oral habits, muscle tension, general condition, emotional stress, and the measurement method [34]. In many studies, 600 N is applied as it is assumed to be the maximum bite force, but other studies have been reported that the maximum bite force ranges from 70 to 500 or 700 N [35]. The static loading method did not properly reproduce the fatigue situation, and it did not consider the complex application of various loading when reproducing the occlusal force received during the lateral movement of the teeth.

Second, perfect bonding of base materials and composite resin was assumed, as in other FEA investigations [24,26,36]. However, this assumption does not occur in clinical situation. The bonding interface of the composite resin and base materials can be affected by several clinical factors, such as the filler content of composite resin, the degree of conversion and the extent of water sorption [37]. Considering the above factors comprehensively in the context of other laboratory studies [10,17–19] and clinical studies [2,13] may help to understand the complex behaviors of polymerization shrinkage and stress.

Furthermore, to simplify the 3D model, the periodontal ligament and bone around the tooth were not reproduced, resulting in the exclusion of their flexibility. This omission resulted in an incomplete reproduction of the clinical situation. However, it was assumed that the quantitative effect this had on the stress distribution was insignificant because the applied load in this study was static and the simulation did not include the time-dependent behavior of physiological tooth movement [38].

5. Conclusions

Within the limitations of the present study, which was conducted using 3D FEA assuming isotropic linear elastic behavior of materials, the following conclusions can be drawn:

1. The application of base materials including GIC, low-viscosity resin and tricalcium silicate cement, reduced the marginal stress caused by polymerization shrinkage of composite resin in class II MOD cavities.
2. The different elastic moduli and polymerization shrinkage of the base materials did not influence the stress distribution of the tooth and composite resin.
3. A difference in thickness (0.5 mm and 1.0 mm) in the base material did not affect the stress distribution of the tooth and composite resin.

CRediT authorship contribution statement

Deog-Gyu Seo: Writing – review & editing, Project administration, Methodology, Conceptualization. Jeong-Kil Park: Visualization, Resources, Investigation. Sung-Ae Son: Methodology, Investigation, Formal analysis. Jae-Hoon Kim: Visualization, Software, Resources, Investigation. Mi-Jeong Jeon: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. Min-Kwan Jung: Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization

Ethics declarations

This study was approved by the Research Ethics Committee of the Seoul National University Graduate School of Dentistry (IRB number: S-D20140004).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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