A 3D finite element analysis of stress in the interphase of restoration-tooth structure due to polymerization shrinkage

Shuiwen Zhu, MS, Jianping Fan, PhD, and Cheng Wang, PhD

School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, Hubei Key Laboratory for Engineering Structural Analysis and Safety Assessment, Wuhan, P. R. China

Purpose: The purpose of this paper is to investigate the influence of interphase properties on restored tooth structure due to polymerization shrinkage of resin-based composite.
Materials and Methods: A 3D finite element analysis was performed. The restoration-tooth interface was simulated using solid elements of varying material properties and thicknesses. The stress within the restored tooth structure built up from the polymerization shrinkage of the restorative composite was computed accounting for the time-dependent and visco-elastic behavior of the composite.
Results: It was found that a correlation exists between material and geometry properties at the restoration-tooth interface and higher shrinkage stresses were located at the interphase due to polymerization shrinkage. The development trend of residual stress from polymerization shrinkage in the restored-tooth structure was predicted.
Conclusion: The varying material and geometry properties of restoration-tooth interface seemed to have a conclusive effect on the interfacial stress system, as well as on the longevity of the restoration. From the purely mechanical point of view, this can result in interfacial debonding. **(Int Chin J Dent 2009; 9: 1-8.)**
Key Words: composite restoration, finite element analysis, interphase, polymerization shrinkage.

Introduction

The demand for non-metal tooth restoration has grown considerably in recent years because of their good workability and esthetic appearance. Amongst the most popular alternatives to metal tooth restorations are composite resins and ceramic or composite inlays retained by an adhesive resin. Their main advantages are better aesthetics, avoidance of mercury and lower cost effectiveness. Nonetheless, the stiffness of resin-based composite restorations may vary greatly and does not fully match that of natural teeth. Some problems will appear when the teeth are under stressful conditions. Both polymerization shrinkage[1-3] and cyclical loading[4-6] can disorganize the restoration's coherence.

The major drawback of these restoration techniques probably is the polymerization shrinkage of resin-based composite during the curing process. Shrinkage associated with the polymerization of composite resins can generate considerable stresses in the surrounding tooth tissues. These shrinkage stresses may be confined within the polymerized composite. It can also transfer into the bonding interphase, even the tooth structure, resulting in unknown clinical consequences.[7] When the bonding strength of the adhesive system is insufficient to resist the polymerization shrinkage stress, a gap will develop at the bond interphase, causing marginal leakage of the restoration. On the other hand, although the bonding strength is sufficient to sustain the stress, the stress will transmit to the tooth structure, leading to a cuspal deflection which may in turn result in postoperative hypersensitivity or enamel fracture.[8,9]

Shrinkage stresses are believed to develop mainly within the time periods of irradiation. Such stresses can have a detrimental effect on the longevity of the restoration and the dentin-restoration interphase.[10-13] The use of low modulus restorative materials or the application of flexible adhesive linings has shown to render release of such stresses, which can thus be adopted as a method to reduce composite restoration deterioration.[2,3,14,15] However, utilization of low modulus filling materials is not always possible in stress-bearing areas, and the restoration has to be strong and wear resistant. Therefore, composites with high load-bearing capacity such as high modulus must be used.[16,17] A relatively thick bonding layer of 50-250 μm has been proven to be effective in leveling the mismatch of modulus values at the restoration-tooth interface.[18,19] However, few research articles have been found to optimize the Young's modulus and thickness of the restoration-tooth interphase, the purpose of which is to reduce shrinkage stresses.

The dimensions of the teeth differ from each other, and they exhibit large deviation from the standard mean values. The stress found from simplified laboratory test set-ups may not fully mimic that from the complex clinical cases. For these reasons, different experimental measurements can hardly be compared fairly. However, the influence of the restoration-tooth interface on the stress system generated in the tooth was of interest. The development of tensile and/or shear stresses at the restoration-tooth interface can disrupt the adhesive bonding of the restoration system to the cavity walls and have a detrimental effect on the longevity of the restoration. Finite element analysis (FEA) software has been developed as a tool to investigate the magnitude and distribution of stresses in complex geometries such as restored teeth. This clinical problem has been addressed in finite element models, where variations in the material properties of restoration-tooth interface were investigated for their influence on the stresses induced in the restoration-tooth structure.[17,20] In this study, the mechanical behavior of the enamel-dentin-composite interphase structure, subjected to polymerization shrinkage has been investigated by means of 3D FEA. This study aimed at optimizing the adhesive interphase thickness and flexibility (sufficient stress absorbency) using finite element method. By doing this procedure, we aim to prevent critical interfacial stresses that might lead to premature failure of the adhesively restored tooth due to polymerization shrinkage.

Materials and Methods

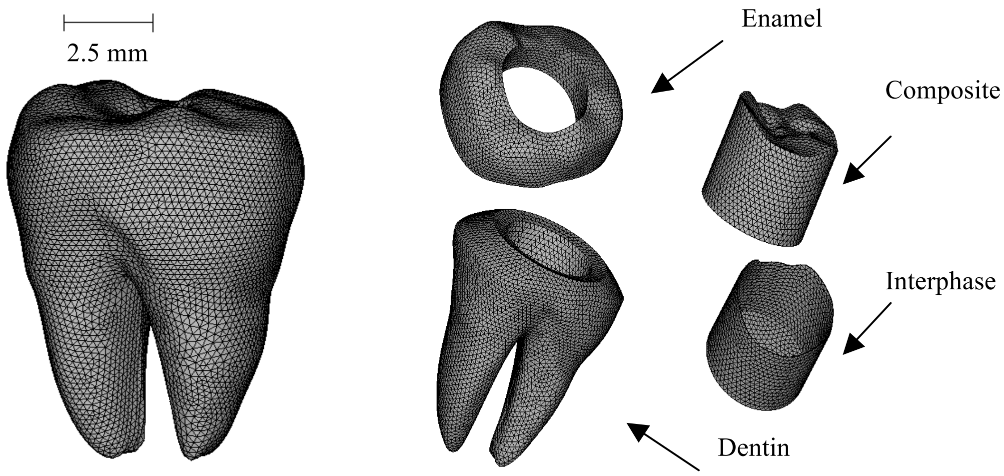
Finite element model

The solid model of a human maxillary premolar was generated using literature data[21] for dentin and enamel internal volumes and morphologies, while the external shape of the maxillary central incisor was obtained by laser based 3D digitizing (Cyberware Inc., Monterey, CA, USA) of a plaster cast (Tanaka Manufacturer, Tokyo, Japan). The scanned profiles were assembled in a 3D wire frame structure using a 3D CAD (AutoCAD 2004, Autodesk Inc., San Rafael, CA, USA). The wire frame curves were exported in a 3D parametric solid modeler (Solidworks 2008, Dassault Systemes, Paris, France). The space for the cavity preparation was also defined. It should be pointed out that the pulp chamber of the tooth was omitted as a simplified calculation because of its negligible stiffness. The restoration was assumed to be bulk filled in one step and fully bonded to the adjacent tooth tissues by the interphase. Some assumptions were made in order to simply the calculations. Absolute bonding was considered among enamel, dentin, composite, and interphase.

The FEA model was obtained by importing the solid model into ANSYS rel. 10.0 FEM software (Ansys Inc., Houston, TX, USA) using IGES format. The volumes were redefined in the new environment and meshed with 4-node tetrahedral elements, finally resulting in a 3D FEA model (Fig. 1). All the nodes on the external surface at the root part were constrained in all directions. Accuracy of the model was checked by convergence tests. Particular attention was devoted to the refinement of the mesh resulting from the convergence tests at the restoration-tooth interfaces. Different material properties were coupled with the elements and geometries according to the volume material defined in Fig. 1 (enamel, dentin, composite, and interphase).

Material properties

All materials except the resin-based composite were considered as linear elastic behavior throughout the entire deformation, which is a reasonable assumption for brittle materials in non-failure conditions.[22] Dentin is a linear elastic and isotropic material while enamel is an elastic and anisotropic material, from a mechanical point of view.[17] However, the anisotropic enamel behavior was neglected in the present study because it has little influence on mechanical behavior of enamel within macroscopic study. Therefore, enamel was assumed to be homogeneous and isotropic.[23] Elastic modulus is 50 GPa for enamel and 18.6 GPa for dentin, whereas Poisson's ratio is 0.3 for enamel and 0.31 for dentin. Young's modulus of the interphase was varied from 0.1 GPa to 50 GPa, corresponding to different clinical materials such as Adper Prompt L-Pop (3M ESPE, Seefeld, Germany), Clearfil Protect Bond (Kuraray, Kurashiki, Japan), and Xeno III (Dentsply, Konstanz, Germany),[24] and Poisson's ratio was set to 0.45 for different materials under consideration.



(a) 3D Finite element model (b) Restoration-tooth system

Fig. 1. Three-dimensional finite element model of the restoration-tooth systems.

The polymerization shrinkage of the composite will generate stress fields within tooth structure, especially within interphase. The data[25] revealed that the stress-strain response is sensitive to the strain rate. This observation suggests that the composite exhibits some sort of viscous behavior, coupled with elasticity. This kind of behavior can be described by means of a relatively simple model consisting of springs and dash-pots. It has been shown that a generalized Maxwell-model consisting of only three sub-models is capable of reproducing the material behavior for the restorative composite.[26] Such model can be implemented easily under the framework of finite element analysis, and is therefore particularly useful for determination of the stress field generated in tooth restoration through numerical simulation. In this study, the stress field generated by the polymerization contraction was evaluated by a way taking the time-dependent and visco-elastic properties of the composite restoration into account.[27,28] The curing time was sub-divided into a large number of small intervals, while Young's modulus, the viscosity and the current polymerization shrinkage were determined for each interval. The properties of resin-based composite were determined as a function of time according to the previous investigation[29] for the restorative composite Clearfill P10. The model used in the present study, together with the associated material properties, Young's modulus, viscosity and shrinkage, are listed in Table 1. It was assumed the polymerization process of the composite finished in 900 seconds, according to the experiment investigation.[26]

Table 1. Time-dependent polymerization parameters for a chemical curing composite.

Time (s)	*E* (MPa)	*η* (GPa)	Volume shrinkage (%)
0	40	60	0
150	40	60	1.25
300	700	774	1.93
450	2140	868.8	2.20
600	3800	1104	2.31
750	4600	2160	2.37
900	5400	3222	2.41

Residual stresses due to polymerization

Polymerization shrinkage of resin-based composites cause residual stresses within restoration-tooth structure, resulting in that the restored tooth is in stressed status even no applied loading after curing. The presence of residual stresses results in a changed behavior of the restored tooth, which may become evident for its clinical performance. Clinical symptoms associated with the residual stress may include inadequate adoption, microcrack propagation, microleakage and secondary caries.[26] The residual stresses (von Mises equivalent stresses) were calculated by the FE method to account for the variations in restoration-tooth interphase material properties and thicknesses. Here, two variations were considered: 1) Changing the material properties of the interphase, Young's modulus E_i, while keeping the thicknesses of the interphase unchanged; and 2) Changing the thicknesses of the interphase while fixing the material properties of the interphase, Young's modulus E_i.

Results

During the polymerization process, the development of the maximum shrinkage stress (von Mises equivalent stress) at different time obtained from the FE calculation are presented in Fig. 2 for studying the influence of different Young's modulus of the interphase and different interphase thicknesses, respectively within 900 s, interphase thickness was kept constant at 0.15 mm in Fig. 2a while Young's modulus was kept unchanged at 10 GPa in Fig. 2b.

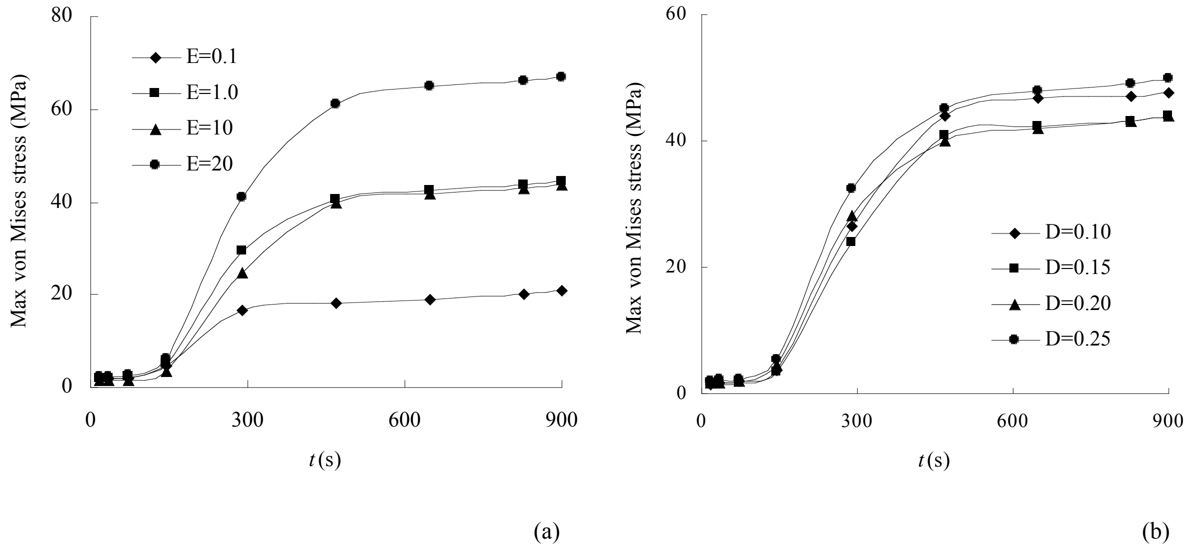
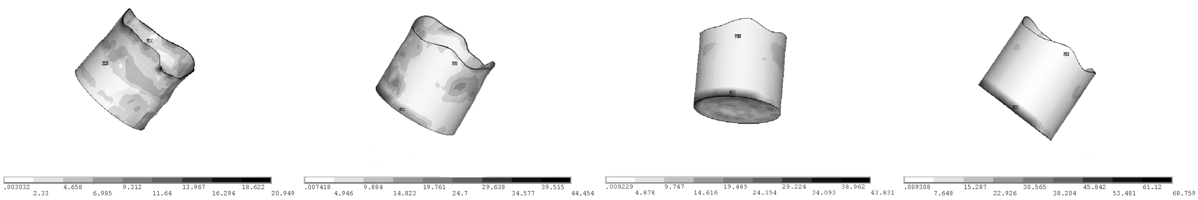


Fig. 2. Time histories of maximum von Mises stress generated in the interphase during the polymerization for (a) different Young's modulus (D=0.15 mm), and (b) different interphase thicknesses (*E*=10 GPa).

These curves representing on-polymerizating processes of composite are usually S-shaped. Generally, the stress generation within the resin-based composite, the tooth and the interphase developed in three stages: 1)

Initially, very little stresses were accumulated due to the viscous behavior of the composite resin (0-150 s); 2) Subsequently, stresses increased more significantly due to polymerization, stiffening and a reduction of visco-elasticity of the composite (150-450 s); and 3) Finally, stresses almost kept unchanged without consideration of stress relaxation (450-900 s). The maximum magnitudes of these stresses were between 20 and 70 MPa. Without considering occulusal loading, it was found that the stresses remain constant in the third phase according to Fig. 2.

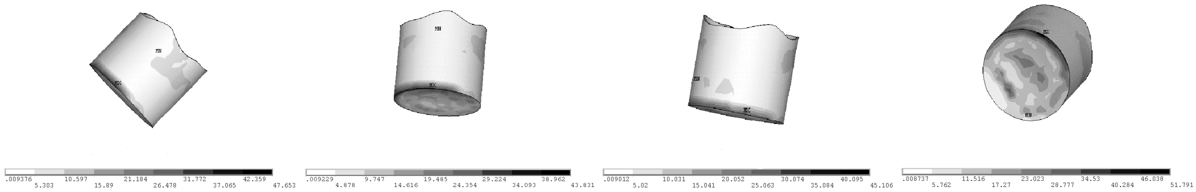
The residual stress (von Mises equivalent stress) distribution contours of the interphase for four different Young's modulus of the interphase: E=0.1, 1, 10, and 20 MPa, are predicted in Fig. 3, in which the thickness of the interphase was kept unchanged at 0.15 mm, and were obtained at the time of 900 s, just after completion of polymerization. It is clear from Fig. 3 that the location of stress concentration resulting from polymerization of the composite was found to occur predominantly at the interphase layer and dentin wall junction, where there was greater curvature, thus prone to stress concentration from a purely mechanical point of view; or the upper surface where interphase and enamel wall meet.



(a) E_i=0.1 GPa (b) E_i=1 GPa (c) E_i=10 GPa (d) E_i=20 GPa

Fig. 3. Residual stress distribution in the interphase with varying Young's modulus of the interphase (D=0.15 mm).

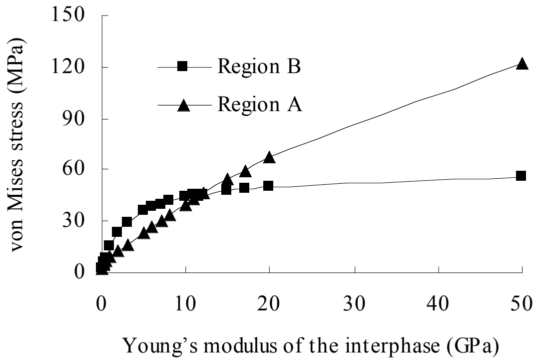
The residual stress (von Mises equivalent stress) distribution contours of the interphase are shown in Fig. 4 for investigating the influence of different interphase thicknesses (D=0.10, 0.15, 0.20, and 0.25 mm) also at 900 s, while Young's modulus of the interphase was kept unchanged at 10 GPa. It was clear from Fig. 4 that the stress concentration resulting from polymerization of the composite was found to occur predominantly at the regions more or less the same as those shown in Fig. 3.



(a) D=0.10 mm (b) D=0.15 mm (c) D=0.20 mm (d) D=0.25 mm

Fig. 4. Residual stress distribution in the interphase with varying interphase thicknesses (E=10 GPa).

It is found that high residual stresses are located at the occlusal surface along the tooth-composite joint (region A) and line angle surrounding the pulpal wall (region B) of the interphase in the present model. Fig. 5 shows the effects of Young's modulus of the interphase on the residual stress in the interphase developed at the afore-mentioned regions at 900 s. From Fig. 6, the maximum residual stress occurs in the region B when Young's modulus of the interphase is varied between 0.1 GPa and 10 GPa, while, when Young's modulus of the interphase increases, the maximum residual stress occurs in the region A. The residual stress in the region A and region B of the interphase increase with increasing Young's modulus of the interphase.



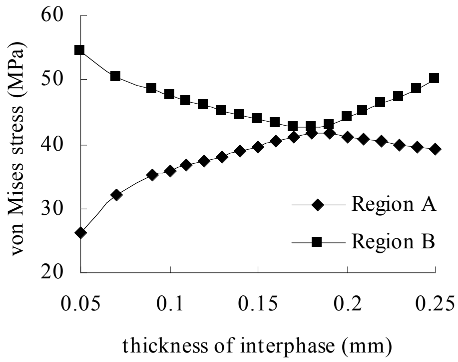


Fig. 5. Residual stresses generated in the interphase with different Young's modulus of the interphase at 900 s after curing (left).
Fig. 6. Residual stresses generated in the interphase with different thicknesses of interphase at 900 s after curing (right).

Fig. 6 illustrates the effects of the different interphase thicknesses on the residual stress in the interphase developed in the region A and region B only at 900 s. From Fig. 6, the residual stress increases firstly in the region A when the thickness of the interphase increases, then decreases when the thickness of the interphase increases further, on the contrary, the residual stress decreases firstly in the region B when the thickness of the interphase increases, then increases when the thickness of the interphase increases further. It can also be seen that the high residual stress value in the region B is still larger than the value in the region A during the thickness of interphase changing. When the thickness of the interphase increases up to about 0.18 mm, the maximum residual stress value becomes lowest according to Fig. 6.

Discussion

Filling decayed teeth with restorative materials has been a conventional method for a long time. The polymerization shrinkage process happened within the resin-based composite at an early stage of restoration, followed by occurrence of a more complicated process. Fig. 2 shows that the process can be divided into three different phases: 1) a viscous behavior phase; 2) a reduction of visco-elasticity behavior phase; and 3) an elastic behavior phase. Microcracking and interfacial failure may occur due to residual stress, or as a result of resin-based composite polymerization. A possible means of improving the mechanical performance of the interphase is to extend the curing time of simplified interphase beyond those recommended by the manufacturers, which can result in improved polymerization and reduced permeability.[30]

Figs. 3 and 4 show the residual stress distribution in the interphase in details at the moment when the polymerization of the resin-based composite has completed. Considering the effect of only polymerization shrinkage, the highest stresses are observed in the vicinity of the top surface and near the interface or at the interphase layer and dentin wall junction where greatest curvature usually occurs. Some research studies have shown that, when the residual stress in the interphase, reached a certain value, fracture and voids would occur in this region.[31] The marginal gap between the composite and tooth appears, and the integrity of the restoration-tooth structure can eventually be destroyed when the highest stresses are in the vicinity of the top surface and near the interfaces.[32] Bacteria may find an opportunity to gain access to the space between the filling and the tooth. This phenomenon is known as microleakage. When it occurs, tooth-brushing process can hardly remove these bacteria, and their metabolic activity leads to extensive decay within the tooth, which is the so-called secondary caries. Therefore, it is very crucial for a dentist to select an interphase with appropriate stiffness and thickness so as to make sure that no interphase failure and aforesaid consequences will happen. This study confirms that the application of the interphase with a lower elastic modulus and a higher thickness can provide a benefit of relieving upper surface stress of the interphase arisen from the polymerization shrinkage. But, from the findings in the present study, it is easily found that the stress at the interphase layer and dentin wall junction increases as the thickness of interphase increasing, which may result in microleakage within the restored teeth. Some research studies have shown that the property of the restorative composite has more influence on the displacement while the interphase has little when considering the effect of polymerization shrinkage.[33]

The development trend of the residual stress with varying Young's modulus of the interphase has been shown in Fig. 5, in which the region A and region B represent the different locations in the restored teeth with high shrinkage stress. From these results, the interphase with Young's modulus of 10-20 GPa is a proper choice. For the developing trend of the residual stress with varying thickness of the interphase shown in Fig. 6, the appropriate thickness of the interphase is about 0.18 mm. Hence, following the findings in the present study, a proper choice of the interphase with appropriate Young's modulus and thickness can help minimize the residual stress in the restorative composite.

The restoration-tooth interphase thickness and rigidity (Young's modulus) are important for restoration-tooth mechanical behavior. A 3D FE analysis has been successfully used to compute the residual stresses (von Mises equivalent stress) in adhesively restored tooth, during polymerization and post-polymerization, respectively. It has been demonstrated that structurally modified teeth show a complex biomechanical behavior during the early stage of the restoration. The FE result shows that the restoration-tooth Young's modulus has opposite effects on the stress relief on the restored tooth: the more rigid the interphase is used in the restored-tooth, the higher the polymerization shrinkage stress is. An appropriate way to limit the intensity of the stress transmitted to the remaining natural tooth tissue is to employ an adhesive interphase of a certain thickness and a certain Young's modulus, which is able to partially adsorb the composite deformations. From the current findings, a thin interphase of a more flexible adhesive (lower Young's modulus) exhibits the same mechanical performance as a thick interphase of a less flexible adhesive (lower Young's modulus) for the restored teeth. The present study can form a good basis for further investigation and provide some guidance for clinical application of the restorative composite and interphase materials.

Acknowledgment

The authors wish to thank the substantial support from the Research Fund for the Doctoral Programs of the Higher Education of PRC (No. 20070487066).

References

1. Shimizu A. An in vitro investigation of the tooth strains associated with four different restorations in class II cavity. J Prosthet Dent 1996; 76: 309-14.
2. Kinomoto Y. Comparison of polymerization contraction stresses between self- and light-curing composites. J Dent 1999; 27: 383-9.
3. Dauvillier BS. Visco-elastic parameters of dental restorative materials during setting. J Dent Res 2000; 79: 818-23.
4. Fissore B. Load fatigue of five restoration modalities in structurally compromised premolars. Int J Prosthodont 1995; 8: 213-20.
5. Fissore B. Load fatigue of teeth restored by a dentin bonding agent and a posterior composite resin. J Prosthet Dent 1991; 65: 80-5.

6. Ausiello P, Davidson CL, Cascone P, De Gee AJ, Rengo S. Debonding of adhesively restored deep class II MOD restorations after functional loading. Am J Dent 1999; 12: 84-8.
7. Sue HL, Juhea C, Jack F, In BL. Influence of instrument compliance and specimen thickness on the polymerization shrinkage stress measurement of light-cured composites. Dent Mater 2007; 23: 1093-100.
8. Carvalho RM, Pereira JC, Yoshiyama M, Pashley DH. A review of polymerization contraction: the influence of stress development versus stress relief. Oper Dent 1996; 21: 17-24.
9. Opdam NJ, Roeters FJ, Feilzer AJ, Verdonschot EH. Marginal integrity and postoperative sensitivity in class 2 resin composite restorations in vivo. J Dent 1998; 26: 555-62.
10. Davidson CL, De Gee AJ, Feilzer AJ. The competition between the composite-dentin bond strength and the polymerization contraction stress. J Dent Res 1984; 63: 1396-405.
11. Ensaff H, O'Doherty DM, Jacobsen PH. Polymerization shrinkage of dental composite resins. Proc Inst Mech Eng [H] 2001; 215: 367-75.
12. Watts DC, Marouf AS, Al-Hindi AM. Photo-polymerization shrinkage-stress kinetics in resin-composites: methods development. Dent Mater 2003; 19: 1–11.
13. Palin WM, Fleming G, Nathwani H, Burke T, Randall RC. In vitro cuspal deflection and microleakage of maxillary premolars restored with novel low-shrink dental composites. Dent Mater 2005; 21: 324–35.
14. Kemp-Scholte CM, Davidson CL. Setting stress in composite resin in relation to configuration of restoration. J Dent Res 1987; 66: 1636-9.
15. Davidson CL, Abdalla AI. Effect of thermal and mechanical load cycling on the marginal integrity of class II resin composite restorations. Am J Dent 1993; 6: 39-42.
16. Davidson CL. Resisting the curing contraction with adhesive composites. J Prosthet Dent 1986; 55: 446-7.
17. Peters MC. Comparison of two measurement techniques for clinical wear. J Dent 1999; 27: 479-85.
18. Davidson CL, Davidson-kaban SS. Handling of mechanical stresses in composite restorations. Dent Update 1998; 25: 274-9.
19. Magne P. Effect of luting composite shrinkage and thermal loads on the stress distribution in porcelain laminate veneers. J Prosthet Dent 1999; 27: 383-9.
20. Ausiello P, Apicella A, Davidson CL. Effect of adhesive layer properties on stress distribution in composite restorations---a 3D finite element analysis. Dent Mater 2002; 18: 295-303.
21. Wheeler RH. Dental anatomy, physiology and occlusion. Philadelphia: WB Saunders; 1974. p.151.
22. Rees JS, Jacobsen PH. Modelling the effects of enamel anisotropy with the finite element method. J Oral Rehabil 1995; 22: 451-4.
23. Rees JS, Jacobsen PH. The effect of cuspal flexure on a buccal class V restoration: a finite element study. J Dent 1998; 26: 361-7.
24. Osnat F, Shlomo M, Hagay S, et al. Antibacterial properties of self-etching dental adhesive systems. J Am Dent Assoc 2007; 138: 349-54.
25. Feilzer AJ, De Gee AJ, De Gee CL. Quantitative determination of stress reduction by flow in composite restorations. Dent Mater 1990; 6: 167-71.
26. Hubsch PF, Middleton J, Feilzer AJ. Identification of the constitutive behaviour of dental composite cements during curing. Comput Method Biomech Biomed Eng 1999; 2: 245-56.
27. Bill K, Andrei K, Krzysztof B. Effect of material properties on stresses at the restoration-dentin interface of composite restorations during polymerization. Dent Mater 2006; 22: 942-7.
28. Richard S, Michael G, Mario P, Vitus S. On the effect of an internal light conductor on the marginal integrity of class-II composite fillings. Dent Mater 2007; 23: 145-52.
29. Barink M, van der Mark PCP, Fennis WMM, Kuijs RH, Kreulen CM, Verdonschot N. A three-dimensional finite element model of the polymerization process in dental restorations.Biomaterials 2003; 24: 1427-35.
30. Lorenzo B, Annalisa M, Alessanadra R, Milena C, Roberto DL, Elettra DSD. Dental adhesion review: Aging and stability of the bonded interface. Dent Mater 2008; 24: 90-101.
31. Fan JP, Tang CY. The influence of shrinkage and moisture diffusion on idealized tooth structure involving debonding damage. Acta Mech Sol Sin 2005; 18: 110-20.
32. Roberto RB, Rafael YB, Jack LF. Factors involved in the development of polymerization shrinkage stress in resin-composites: A systematic review. Dent Mater 2005; 21: 962-70.
33. Li J, Li HY, Fok SL. A mathematical analysis of shrinkage stress development in dental composite restorations during resin polymerization. Dent Mater 2008; 24: 925-31.

Correspondence to:

Dr. Jianping Fan
School of Civil Engineering and Mechanics, Huazhong University of Science and Technology
1037 LuoYu Road, HongShan District, Wuhan, Hubei Province 430074, P. R. China
Fax: +86-27-87543501 E-mail: jpfan@mail.hust.edu.cn

Received March 10, 2009. Accepted March 19, 2009.