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Shrinkage behaviors of dental composite restorations—The experimental–numerical hybrid analysis

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ABSTRACT

Objectives. To investigate the effects of light curing protocols on the shrinkage behaviors, contraction stress, and microleakage in composite restorations by an experimental–numerical hybrid analysis.
Methods. Three groups of human molars were collected to receive different light-curing protocols: vertical or oblique curing at regular intensity, and vertical curing at reduced intensity. For each tooth, the composite fillings were consecutively placed under unbonded and bonded states, and their shrinkage behaviors were examined with a digital image correlation (DIC) technique. The strains of the unbonded restorations were input into two finite element analysis (FEA) models with settings of the composite as either homogeneous or hardened along polymerization gradients. The preliminary solutions were verified by their individual deformations in the bonded restorations. The interfacial microleakage of restorations was also determined by micro-CT scanning and compared with the FEA results.
Results. The bonded restorations showed centripetal shrinkage patterns with greater downward displacements than their unbonded restorations. Vertical curing at regular intensity caused the greatest shrinkage strain, contraction stress, and microleakage among the three protocols. Low-intensity curing reduced overall shrinkage strain and displacements at cervical margin, but did not prevent the formation of microleakage. Oblique curing caused asymmetric shrinkage with the tooth-shielded side revealing less deformation. Setting the polymerization-dependent elastic moduli of the composite enhanced the reliability of FEA.
Significance. This hybrid analysis comprehensively examined the polymerization shrinkage behaviors. Both the light intensity and direction affect the shrinkages and contraction stress. Oblique curing decreases shrinkage due to the attenuated irradiation by tooth-shielding rather than modulations of shrinkage direction.

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1. Introduction

Resin-base composites are the most popular restorative materials, and are used in a variety of dental applications. However, their shrinkage with polymerization can cause internal stresses and interfacial defects [1]. Resin composites shrink centripetally toward the center at their unbounded state, and their free volumetric shrinkage primarily depends on their composition and degree of conversion (DC) [2,3]. In dental cavities, the composites are bonded and constrained to develop various shrinkage patterns. The shrinkage behaviors are influenced by the material properties (elasticity and viscoelasticity) [1], light-curing conditions (light intensity, energy density, and direction) [2,4,5], filling techniques [6], and may reflect the reaction kinetics of polymerization [4]. In general, these behaviors are the critical results of competition between the composite-tooth adhesion and contraction stress [5]. Once the contraction stress exceeds the bond strength, interfacial separation or microleakage occurs at these weak-bonded areas. The influences of light curing protocols on both the shrinkage strain and build-up of contraction stress in composite restorations has been recognized in previous studies [2,4,5,7,8], and shown to be related to the occurrence of immediate or postoperative restorative failure [9–11].

Various approaches have been applied to assess the shrinkage behaviors and their dynamic changes in relation to polymerization kinetics, with the bonded disc method adopted in many investigations [2,12]. A similar experimental setting has been also developed to plot the shrinkage profiles on flat composite materials by using a stylus-dial gauge system [13]. However, the shrinkage behaviors in dental cavities are more complex than these extra-cavity measurements. The investigation of stress–strain kinetics is a difficult task, unless the measurements provide the spatially resolved information. The digital image correlation (DIC) method has recently been used to analyze the contraction behaviors of dental composites in either free shrinkage or restoration form. By comparing two images obtained at different states, the displacements and displacement gradients of certain points can be computed based on the assumptions of pattern matching on characterized subjects [14,15]. The DIC-assisted measurements aid in assessing both the temporal and spatial dependence of shrinkage strain [16], and also demonstrate the global contraction fields of the composite restorations [17–19]. Their results can also be input into numerical analysis to validate the simulations, via this approach the contraction stress is explored [18]. The combination of DIC-experiment and numerical analysis enables the assessment of multiple influencing variables, and further evaluates their individual roles or interactions with regard to the shrinkage kinetics.

Finite element analysis (FEA) has become an valuable tool in examining the shrinkage deformations [5] or the magnitude and distribution of contraction stresses [20]. A virtual FEA simulation requires modeling the geometries, materials, and loading/boundary conditions. For the cases of polymerization shrinkage, the settings of the material property should consider the shrinkage strain of composites, their associated stiffness changes, and gradient polymerization at different depths of the restorations. The principal difficulty in studying the shrinkage behavior is that the polymerization process varies with the light-curing conditions, and is also modified by the complex anatomic configuration of composite restorations. The light irradiation is partially shielded by the surrounding tooth, while enamel and dentin allow different degrees of light transmittance. Accordingly, assignment of virtual shrinkage strain in FEA needs complicated examinations of the light penetration and DC when the curing regime changes. For most studies, assumptions are given to simplify the settings and make the solving process possible. In early 2-D FEA studies, Versluis et al. solved the proposition of shrinkage-stress analysis via comprehensive examinations of experimental parameters [5,6]. By inputting measurements, including the gradient DC and shrinkages in the restorations, material properties of composites (the elastic modulus and Poisson's ratio), light transmissions through tooth substances, the settings of the FEA were refined to simulate the polymerization reaction. Even with these complicated processes, the results did not completely correspond to the real situation, due to the lower impedance of irradiance by the sectioned tooth cusps. However, these studies did reveal the significance of the experimental data in increasing the accuracy of FEA.

Developing an investigation model by combining DIC and FEA could be an effective approach to investigate the shrinkage-stress states of composite restorations. Our previous work has shown that DIC supports observation of the shrinkage field, which facilitates the validation of FEA [19]. Moreover, the measured shrinkage strain at different locations [18] and under various restorative conditions [18,19] can be extracted as the given material properties or initial conditions. The integration of the experimental and numerical methods is expected to solve complex proposition of polymerization with high accuracy, while avoiding uncertainty and complicated procedures in setting the constitutive conditions.

Numerous methods have been proposed to reduce or modulate the contraction stress and the associated marginal and interfacial failures, especially with regard to modifying the light-curing. The concept of guided polymerization shrinkage is based on the assumption that the contraction of the photo-activated composite is directed towards the light source [21,22]. An alternative method was later proposed by placing the composite increments obliquely and polymerizing through the tooth walls, in order to minimize shrinkage and improve the adaptation of composites [23]. The phenomenon of shrinkage toward the light source has been shown by several experimental analyses [13,24]. However, some investigators considered that this technique worked due to the light impedance by the tooth rather than the alteration of shrinkage vectors [25]. As a consequence of slow polymerization, relaxation of contraction stresses may occur to prevent the interfacial failure. In the last decade, there has been growing support for light irradiation at an initial low intensity or reduced rate, known as the "soft start" curing mode [26,27]. Low irradiation energy during the start of polymerization may decrease post-gel shrinkage strain and stress, prevent the cusp deformation, and enhance the marginal integrity [28–30]. The polymerization kinetics for these two approaches is difficult to assess in laboratory experiments, or simulate by an FEA without complicated settings. In this study, we thus attempted to develop a hybrid experimental–numerical model to examine