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Research Paper

Modeling of damage driven fracture failure of fiber post-restored teeth

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ABSTRACT

Mechanical failure of biomaterials, which can be initiated by either violent force, or progressive stress fatigue, is a serious issue. Great efforts have been made to improve the mechanical performances of dental restorations. Virtual simulation is a promising approach for biomechanical investigations, which presents significant advantages in improving efficiency than traditional in vivo/in vitro studies. Over the past few decades, a number of virtual studies have been conducted to investigate the biomechanical issues concerning dental biomaterials, but only with limited incorporation of brittle failure phenomena. Motivated by the contradictory findings between several finite element analyses and common clinical observations on the fracture resistance of post-restored teeth, this study aimed to provide an approach using numerical simulations for investigating the fracture failure process through a non-linear fracture mechanics model. The ability of this approach to predict fracture initiation and propagation in a complex biomechanical status based on the intrinsic material properties was investigated. Results of the virtual simulations matched the findings of experimental tests, in terms of the ultimate fracture failure strengths and predictive areas under risk of clinical failure. This study revealed that the failure of dental post-restored restorations is a typical damage-driven continuum-to-discrete process. This approach is anticipated to have ramifications not only for modeling fracture events, but also for the design and optimization of the mechanical properties of biomaterials for specific clinically determined requirements.

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1. Introduction

Biomechanics is a major issue that has been comprehensively investigated in dentistry. Innovations of materials or techniques aim to improve the mechanical performances of biomaterials. However, fracture of either teeth tissues or restorative materials is still the most frequent cause of degradation and failure of dental restorations. Long-term promising prognosis is the ultimate goal in dentistry (Stockton, 1999).

In vivo or in vitro studies, such as fracture failure test combined with fractographic investigation, are frequently used to assess the mechanical performances of restorative systems (Keulemans et al., 2009; Schmage et al., 2009; Salameh et al., 2008). Data from these studies can obtain the fracture failure load and final status of teeth fracture, which can partially represent the failure results. However, such studies are time consuming and do not reveal the entire failure process. Moreover, the fracture failure loads obtained from these in vitro studies are always beyond the average occlusal force by three to fivefold, which is inaccurate compared with the clinical situation. Therefore, transfer of these results to clinical practice is questionable.

Reliable evaluation of the mechanical and clinical performances of dental restorations should simulate the oral environments and agree with the clinical process. The finite element method (FEM) is a promising approach for investigating the biomechanics in dentistry. It has been used as an effective tool for assessing the biomechanical responses of complex biological structures, which exhibit highly irregular geometry, diverse design variations, complex load/boundary conditions, as well as non-linear and orthotropic material behaviors. To provide detailed mechanical responses, data extrapolated from virtual analysis can predict the clinical outcomes and be confirmed by clinical investigations.

Experimental and clinical data showed that post-restored teeth have higher risk of mechanical failure than other types of restorations (Shahrbaf et al., 2007; Lin et al., 2011; Sedgley and Messer, 1992). A considerable number of finite element analyses (FEAs) have documented the influence of various factors on the longevity of post-restored teeth, such as cementation techniques (Dejak and Młotkowski, 2011; Wang et al., 2008), residual dentin qualities (Peroz et al., 2005; Akkayan, 2004), and post materials (Asmussen et al., 2005; Boschian et al., 2006; Sorrentino et al., 2007; Buttel et al., 2009). Despite providing important data regarding stress distribution, most of these studies did not accommodate failure criteria or fracture mechanics theory. A hypothesis that the structure remains intact during the whole loading period was often adopted in virtual analysis. However, the fracture of residual dentin or loosening of the post-core assembly is the most frequent mode of failure of post-restored teeth in clinical practice (Maceri et al., 2007; Ng et al., 2006). Thus, this hypothesis clearly misrepresents the actual fracture process under clinical situations.

Accuracy of numerical simulations depends on the construction of appropriate finite element (FE) models and meticulous simulation processes (Schmitter et al., 2010). Given that ultimate mechanical failure is often initiated by small deformation, and consequently accelerated by destruction at the interfaces (Li et al., 2004; Zhang et al., 2015), a full understanding of stress fields developed in the post-restored restorations and the progress of the damage might contribute more importance to assess the variables of post-restored restorations.

To improve understanding of the failure mechanism of post-restored teeth, a novel approach is presented in this paper for the investigation of the fracture failure process using nonlinear analysis of FEM in an explicit framework that incorporates fracture mechanics theory. The William–Warnke model of material failure criteria (Saeed et al., 2012; Turgay et al., 2009) was used to predict the failure of brittle materials on the ANSYS platform (ANSYS Inc., Canonsburg, PA, USA). The criterion for failure caused by a multiaxial stress state can be expressed follows:

$$F/f_c - S \geq 0$$

where F is a function of the principal stress state (σ_{xp}, σ_{yp}, σ_{zp}), $\sigma_1 = \max(\sigma_{xp}, \sigma_{yp}, \sigma_{zp})$, $\sigma_3 = \min(\sigma_{xp}, \sigma_{yp}, \sigma_{zp})$, and $\sigma_1 \geq \sigma_2 \geq \sigma_3$. f_c is the uniaxial compressive strength, and S is the failure surface expressed in terms of principal stresses (Appendix A). The failure surface can be specified with a minimum of two constants, f_t and f_c, which can be obtained using uni-axial tension and uni-axial compression tests. The other three constants (f_{cb}, f_1, and f_2) were set as default according to the William–Warnke model:

$$\begin{cases} f_{cb} = 1.2 f_c, \text{ ultimate biaxial compressive strength} \\ f_1 = 1.45 f_c, \text{ ultimate compressive strength for a state of biaxial compression} \\ f_2 = 1.725 f_c, \text{ ultimate compressive strength for a state of uniaxial compression} \end{cases}$$

When stress combination reaches failure surface and all the principal stresses are compressive stress, the element enters into crushing state and the stiffness of the element is decreased closely to zero. Similarly, if the principal stress is tensile stress, the element enters the cracking state. The smeared crack model is used in ANSYS, allowing maximum of three mutually perpendicular cracks at each Gaussian integral point. Different constitutive matrixes are defined according to the state of crack. For both concrete and dental cements, the default values are considered valid for stress states when the condition is satisfied because this condition applies to a stress situation with a low hydrostatic stress component.

$$\left|\sigma_h\right| \leq \sqrt{3} f_c$$

$$\sigma_h = \text{hydrostatic stress state} = 1/3(\sigma_{xp} + \sigma_{yp} + \sigma_{zp})$$

Meanwhile, the solid 65 element was adopted in the construction of cement layers. The most important aspect of solid 65 is the treatment of nonlinear material properties, such as cracking, crushing, plastic deformation, and creep (ANSYS help system). The solid 65 element has been widely used in the concrete industry to predict the crack and damage behaviors of concrete (Erduran and Yakut, 2004; Li and Wang, 2010; Sakar et al., 2014). It is defined by eight nodes with three degrees of freedom at each node: translations in the nodal x, y, and z directions. The solid 65 element is capable of directional integration point cracking and crushing, as well as incorporating plastic and creep behavior. The reinforcement (which also incorporates creep and plasticity) has