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Fatigue failure of dentin–composite disks subjected to cyclic diametral compression

Yuping Li[a], Carola Carrera[a,b], Ruoqiong Chen[b], Jianying Li[a], Yungchung Chen[a], Patricia Lenton[b], Joel. D. Rudney[b], Robert S. Jones[c], Conrado Aparicio[a], Alex Fok[a,*]

[a] *Minnesota Dental Research Center for Biomaterials and Biomechanics (MDRCBB), School of Dentistry, University of Minnesota, MN, USA*
[b] *Department of Diagnostic and Biological Sciences, School of Dentistry, University of Minnesota, MN, USA*
[c] *Department of Developmental and Surgical Sciences, School of Dentistry, University of Minnesota, MN, USA*

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ABSTRACT

Objective. Our aim was to establish the relationship between cyclic loading and fatigue life of the dentin–composite interface using the newly developed disk in diametral compression tests. The results were then used to estimate the fatigue life of restored teeth under occlusal loading.
Methods. Disk specimens (5 mm dia. × 2 mm thick) were prepared using bovine incisors and restored with either a methacrylate-based composite Z100™ with Adper Single Bond Plus (Z100) or silorane-based composite Filtek™ LS with LS System adhesive (LS). The dentin–composite disks were tested under cyclic diametral compression to determine the number of cycles to failure (N_f) at three load levels ($n = 3$ per group). Finite element analysis (FEA) was used to calculate the interfacial stresses (σ) within the specimen, to establish the σ vs. N_f curves, and those within a restored tooth under normal chewing forces (15 N maximum). These were then used to estimate the lifetime of the restored tooth for the two restorative systems.
Results. The disks restored with LS had a higher fatigue resistance than those restored with Z100. The maximum interfacial stress in the restored tooth determined by FEA was ~0.5 MPa. Based on the estimate of 300,000 cycles of chewing per year, the predicted lifetime under occlusal loading for teeth restored with LS and Z100 was 33 and 10 years, respectively.
Significance. The disk in cyclic diametral compression has been used successfully to provide fatigue data which allows the lifetime of composite-restored teeth under occlusal loading to be predicted using numerical simulation.

* *Corresponding author at*: 16-212 Moos Tower, 515 Delaware Street, S.E., Minneapolis, MN 55455, USA. Tel.: +1 612 625 0950; fax: +1 612 626 1484.
E-mail address: alexfok@umn.edu (A. Fok).
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1. Introduction

Resin based dental composites are now widely used for both anterior and posterior restorations. Their comparable mechanical properties to dentin [1,2], ability to bond to tooth tissues and superior esthetics make them more favorable than amalgam as a restorative material [3]. Adhesive systems are used to bond the composite to enamel and dentin. For the latter, the impregnation of the demineralized collagen fibrils with a bonding resin is a major factor in the formation of adhesion [4]. While the initial tooth–composite bonds may be adequate, continuous challenges from mastication [9], hydrolysis and biofilm attacks can degrade the interface, thus resulting in debonding. Secondary caries and fracture of the restoration or tooth, which are the major reasons for the replacement of resin composite restorations, may then follow.

Failures that occur over time as a result of cyclic and/or sustained loading are well recognized clinical problems associated with mineralized tissues [5–7]. A typical method for quantifying the fatigue behavior of a material is the stress-life approach which relates the number of cycles to failure (N_f) to the stress amplitude (σ). The measured fatigue lifetime represents the number of cycles to cause failure through unstable crack growth. Mineralized tissues such as dentin and enamel display typical σ–N_f curves in that N_f decreases with increasing σ [8,9]. Clinically, one of the main reasons for the failure of dental restorations is also cyclic fatigue associated with mastication. Being able to quantify the degradation of the tooth–restoration interface in the oral environment can therefore help to predict the lifetime of composite restorations. While the fatigue failure mechanisms of interfaces between composites and tooth tissues are expected to be different from those of the constituents, they display similar σ–N_f curves. There are relatively few investigations that focus on the cyclic fatigue of the tooth–composite interface [10–14], probably because they can be very expensive and time-consuming to perform, even using laboratory testing to simulate the occlusal load. A more efficient strategy, as widely used in engineering, would be to use numerical modeling, coupled with the σ–N_f data, to predict the lifetimes of dental restorations.

The aims of the present study were, therefore, to (1) determine the σ–N_f curve, i.e. the fatigue strength, for the composite–dentin interface using the newly developed composite–dentin disk specimen under diametral compression [15]; and (2) use this interfacial fatigue data to predict the lifetime of composite-restored teeth under physiological conditions. The composite–dentin disk in diametral compression has previously been used successfully to evaluate the static bond strength between these materials [15].

2. Materials and methods

2.1. *Preparation of dentin–composite disks*

Dentin–composite disks were prepared using the method reported previously [15]. Briefly, roots from bovine incisors were obtained by removing the crowns at the cemento-enamel junction. They were then trimmed into dentin cylinders of 5 mm in diameter, with the root canals enlarged concentrically to 2 mm in diameter. The dentin cylinders thus produced were randomly divided into two groups and restored with one of two composites (Z100™ and Filtek™ LS, both from 3M ESPE, St. Paul, MN, USA) using the corresponding adhesives as per the manufacturer's instructions. These two composites were chosen because they have different polymerization chemistries and use different adhesive systems. Z100 is a conventional methacrylate-based composite and it uses a total etch and rinse adhesive system. It exhibits high volumetric shrinkage of over 2% after curing [16]. In contrast, Filtek™ LS is a silorane-based composite with less than 1.0% total volumetric shrinkage [17], and it uses a self-etch adhesive system. For specimens restored with the Z100 system, the inner dentin surface was etched with 35% phosphoric acid for 20 s and then rinsed with deionized water. Two layers of adhesive (Adper™ Single Bond Plus, 3M ESPE) were applied to the etched surface and cured for 20 s. To minimize shrinkage stress, Z100 composite was applied incrementally to fill the cylinders. Each increment, less than 2-mm thick, was cured for 40 s to ensure adequate curing. For specimens restored with the LS system, a layer of Self-Etch Primer (LS System Adhesive, 3M ESPE) was first applied to the inner dentin surface and cured for 10 s. This was followed by the application of a layer of Bond (LS System Adhesive, 3M ESPE) with 20 s of curing. LS composite was then applied incrementally and cured in the same way as Z100. Finally, the composite-restored cylinders were transversely cut to produce 2-mm thick round disks. All restorative materials were cured using a LED light-curing unit (Elipar™ S10, 3M ESPE) with a power density of 1200 mW/cm^2. During curing, the tip of light guide was held as close as possible to the materials without touching them. The compositions and product information of the composites and adhesive bonding systems are described in Table 1.

2.2. *Fatigue testing*

The prepared disks were loaded to failure in cyclic diametral compression using a universal testing system (MTS 858 Mini Bionix II, Eden Prairie, MN, USA) operated with load control (Fig. 1a). Cyclic diametral compression at 1 Hz with a square wave of zero minimum load was applied to the specimens in deionized water at room temperature. The load and displacement were monitored continuously throughout the whole cyclic loading process. The number of cycles to failure (N_f) was determined from a dramatic change in the displacement patterns (Fig. 1b). The static fracture load of both Z100- and LS-restored disks had previously been found to be approximately 400 N [15]. For the current fatigue test, three load levels, with 50%, 37.5% and 25% of the static fracture load as the peak value, were applied, and three samples for each material group were evaluated at each load level. The use of such a small sample size was justified because the uncertainties in the parameters derived for the fatigue models were reasonably small (see standard errors in Fig. 6). The stress-life (σ–N_f) curves were constructed by first determining the maximum interfacial tensile stress within the disk using finite element analysis (FEA, see later) with the peak load and then plotting the stress against the number of cycles to failure.