Accelerated fatigue testing of dentin-composite bond with continuously increasing load

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ABSTRACT

Objectives. The aim of this study was to evaluate an accelerated fatigue test method that used a continuously increasing load for testing the dentin-composite bond strength.

Methods. Dentin-composite disks ($\phi 5\,mm \times 2\,mm$) made from bovine incisor roots were subjected to cyclic diametral compression with a continuously increasingly load amplitude. Two different load profiles, linear and nonlinear with respect to the number of cycles, were considered. The data were then analyzed by using a probabilistic failure model based on the Weakest-Link Theory and the classical stress-life function, before being transformed to simulate clinical data of direct restorations.

Results. All the experimental data could be well fitted with a 2-parameter Weibull function. However, a calibration was required for the effective stress amplitude to account for the difference between static and cyclic loading. Good agreement was then obtained between theory and experiments for both load profiles. The in vitro model also successfully simulated the clinical data.

Significance. The method presented will allow tooth-composite interfacial fatigue parameters to be determined more efficiently. With suitable calibration, the in vitro model can also be used to assess composite systems in a more clinically relevant manner.

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1. Introduction

Resin composites are now widely used in direct dental restorations. However, as their use becomes more popular, the occurrence of restoration failure has also become more frequent [1,2]. Clinical studies have shown that, on average, composite restorations have a shorter lifetime than amalgam restorations, with one of the main causes of failure being recurrent caries at the tooth-restoration margin [3–5]. Maintenance of interfacial integrity is therefore essential for a composite restoration to be durable, and all new composite systems should be assessed for their interfacial strength to ensure acceptable clinical performance. However, clinical studies can be time-consuming and expensive to perform. Also, in a clinical study, it is hard to control factors such as operator skills, tooth location and anatomy, restoration dimensions, occlusal load, etc. [6–9], making it difficult to identify materials-related factors.

As a result, prediction of the clinical performance of a composite system relies heavily on laboratory bond strength testing using simple specimens, with the tensile and shear test methods being the most common [10,11]. With these methods, static, or fast fracture, tests are usually performed due to the speed at which data can be collected. However, the predictive power of static tests has been questioned as the majority of dental restorations fail under subcritical, cyclic occlusal loads over an extended period of time, during which the interfacial bond degrade progressively. Thus, cyclic fatigue tests should be used to test dental restorations if more reliable assessment is required. For such tests, a constant load-amplitude can be used to test the specimens until failure, or until an acceptably large number of cycles is reached [12,13]. Since dental restorations take years to fail, testing them at the clinical load level may be prohibitively long, even at a frequency higher than that of normal occlusal functions. To expedite the process, therefore, load levels successively higher than that experienced clinically can be used to determine the dependence of the fatigue life on the load level [14]. Predictions can then be made through extrapolation for the clinical situation [15–18]. Alternatively, the step-stress method [19,20] can be used to accelerate the fatigue test. This involves stepping up the load amplitude at specified intervals during each test, with a certain number of cycles applied in between, until failure. In either case, the load levels are usually set at different percentages, e.g., 10, 25 and 50%, of the fast fracture load. The results can then be analyzed using a probabilistic model, giving the survival probability of the specimens or restorations as a function of the number of cycles of loading [21,22].

In this paper, instead of stepping up the load at discrete intervals, a continuously increasingly load is used to fatigue the dentin-composite interface. Dentin-composite discs under diametral compression [17,23] are used to create tensile stresses at the interface to cause debonding. A probabilistic model based on the Weibull function [24] and Basquin's stress–life relationship [25] is also developed to analyze the data. As to be shown, the use of a power function to generate the continuously increasing load allows the fatigue parameters of the interface to be determined readily from the Weibull plot of the experimental data. Finally, an example is presented to demonstrate how the in vitro model can be calibrated using clinical data, so that it can be used to assess composite systems in a more clinically relevant manner.

2. Materials and methods

2.1. Theory

A widely used model for calculating the failure probability of brittle materials or structures such as restored teeth is that based on the Weakest-Link Theory (WLT) [26]. According to this theory, a loaded chain of links fails when its weakest link fails. As a result, survival of the chain depends on the survival of all its links. Mathematically, the WLT can be expressed as

$$P_s = p_{s1} p_{s2} p_{s3} \ldots p_{sn} \tag{1}$$

where P_s is the survival probability of the chain with n links, and p_{si} ($i = 1, 2, 3, \ldots, n$) are the survival probabilities of the links. If all the links are nominally identical and subjected to the same load, we can assume that $p_{si} = p_s$ ($i = 1, 2, 3, \ldots, n$). Then Eq. (1) becomes

$$P_s = p_s^n \tag{2}$$

The Weibull function [24] is usually used to describe the survival probability (p_s) of each link. It has the form:

$$p_s = exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \tag{3}$$

where σ is the load or stress, σ_0 the material's characteristic strength, and m is the Weibull modulus which measures the spread of the failure loads. Substituting Eq. (3) into Eq. (2) gives:

$$P_s = exp\left[-n\left(\frac{\sigma}{\sigma_0}\right)^m\right] \tag{4}$$

from which we can see the so-called size effect, i.e., the longer the chain, the lower its survival probability under a particular load. In general, for brittle materials, the larger the specimens are, the lower their mean strength.

For nominally identical specimens, we can ignore n in Eq. (4) for simplicity, and σ_0 would represent the characteristic strength of specimens of a certain size and shape.

Eq. (4) applies to specimens subjected to a static or monotonically increasing load only. For nominally identical specimens subjected to cyclic loading, a similar equation can be written:

$$P_s = exp\left[-\left(\frac{N_c}{N_f}\right)^\mu\right] \tag{5}$$

where N_c is the number of cycles of loading, N_f is the characteristic life under a particular load, and μ is the Weibull modulus for cyclic fatigue. Using Basquin's model for the characteristic life [25], i.e.,

$$N_f = \left(\frac{\sigma_0}{\sigma_f}\right)^\beta \tag{6}$$

where σ_f is the fatigue stress amplitude, σ_0 the mean stress amplitude that will cause failure in one cycle (which is the same as the static strength), and β the fatigue strength exponent, Eq. (5) can be rewritten as:

$$P_s = exp\left[-N_c^\mu\left(\frac{\sigma_f}{\sigma_0}\right)^{\beta\mu}\right] \tag{7}$$

Note that when σ_f approaches the static failure stress σ, N_c will approach unity, and Eq. (7) will reduce to Eq. (4), with $m = \beta\mu$. Thus, the static and cyclic Weibull moduli are directly proportional to each other via the fatigue strength exponent. Note also that the cyclic stress amplitude (σ_f) depends on the form of the cyclic loading. Specifically, it depends on the ratio