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Fatigue testing of biomaterials and their interfaces[☆]

Dwayne Arola^{a,b,c,*}

^aDepartment of Materials Science and Engineering, University of Washington Seattle, WA, USA

^bDepartments of Oral Health Sciences, School of Dentistry, University of Washington, Seattle, WA, USA

^cDepartments of Restorative Dentistry, School of Dentistry, University of Washington, Seattle, WA, USA

Abstract

Objective—The objective of this article is to describe the importance of fatigue to the success of restorative dentistry, with emphasis on the methods for evaluating the fatigue properties of materials in this field, and the durability of their bonded interfaces.

Methods—The stress-life fatigue and fatigue crack growth approaches for evaluating the fatigue resistance of dental biomaterials are introduced. Emphasis is placed on in vitro studies of the hard tissue foundation, restorative materials and their bonded interfaces. The concept of durability is then discussed, including the effects of conventional “mechanical” fatigue combined with pervasive threats of the oral environment, including variations in pH and the activation of endogenous dentin proteases.

Results—There is growing evidence that fatigue is a principal contributor to the failure of restorations and that measures of static strength used in qualifying new materials and practices are not reflective of the fatigue performance. Results of selected studies show that the fundamental steps involved in the placement of restorations, including the cutting of preparations and etching, cause a significant reduction to the fatigue strength of the hard tissue foundation. In regards to the bonded interface, results of studies focused on fatigue resistance highlight the importance of the hybridization of resin tags, and that a reduction in integrity of the dentin collagen is detrimental to the durability of dentin bonds.

Significance—Fatigue should be a central concern in the development of new dental materials and in assessing the success of restorative practices. A greater recognition of contributions from fatigue to restoration failures, and the development of approaches with closer connection to *in vivo* conditions, will be essential for extending the definition of lifelong oral health.

Keywords

Bonded interface; Cracks; Dentin; Durability; Fatigue; Fracture

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*Correspondence to: Department of Materials Science and Engineering, University of Washington, Roberts Hall, 333, Box 352120, Seattle, WA 98195-2120, USA. Fax.: +1 206 543 3100. darola@uw.edu.

1. Introduction

The failure of structural materials that are designed to withstand mechanical loading can result from a variety of causes. While failures associated with overloads are generally considered first, fatigue is more often the primary mode of failure of load-bearing structures [1]. Fatigue is regarded as the reduction in load-carrying capacity of a material subjected to cyclic stresses and results from an accumulation and growth of damage. As such, conditions that involve repetitive loads warrant consideration of fatigue-related material failures. The cyclic nature of mastication, and the delayed failure of restorations after a period of oral function, clearly suggest that an understanding of fatigue is relevant to the success of restorative dentistry.

A highly cited study concerning the annual incidence fracture in the United States estimated a cost of 119 billion dollars (in 1982 value), which equated then to about 4% of the gross national product [2,3]. The investigation emphasized that this cost could be significantly reduced by including more emphasis on design for resistance to fatigue failures. That could be an equally relevant message for the field of dental materials. But what relevance does a study focused on engineering structures have to the field of dentistry?

The two major reasons for restored tooth failure are recurrent caries and fractures [4–6]. The replacement of failed restorations consumes the majority of a dentist's daily activities. In fact, replacing failed restorations accounts for 50–70% of all clinical work performed [7–10]. This is an important point, as the cost for tooth cavity restorations in the U.S. was nearly \$50 billion in 2005 alone [9]. If even only 10% of restoration failures were attributed to fatigue and could be avoided by better understanding, that would accumulate to an annual savings of billions of dollars. The repair of failed restorations frequently involves the removal of tooth structure and a reduction of the hard tissue foundation available for supporting the subsequent restoration. That reduces the chance of success.

It is essential to acknowledge that fatigue is not a new topic in dentistry. Studies in this area began to appear in the late sixties [e.g. 11,12]. In fact, the fatigue properties of dental composites have received considerable attention for over two decades [e.g. 13–20]. In vitro studies seldom take into account the contributions of fatigue and aging factors, despite their contributions to the formation of cracks and their propagation within the materials placed in the mouth [21]. Yet, this topic appears to be gaining recognition. Indeed, fatigue is now recognized as either the primary mode of failure or a contributing mechanism in the failure of both direct and indirect restoratives [e.g. 22,23].

Fatigue studies involve the application of cyclic loading and require considerably more time than standard strength tests. There is also a general belief that the fatigue strength of a material can be obtained from the static strength, which could reduce the incentive to perform evaluations involving fatigue. This relationship is limited primarily to metals and not necessarily true for other material classes. Indeed, the conventional bulk properties of dental resin composites including the elastic modulus, flexural strength and fracture toughness are reportedly not good indicators of the fatigue resistance [20] and could have

limited clinical relevance. Furthermore, recent assessments of in vitro evaluations and clinical outcomes suggest that the fatigue properties of resin composites may be useful in predicting clinical performance [24,25]. These emerging findings suggest that the fatigue properties of dental materials, and the durability of bonds that maintain them in place, should be considered important metrics of performance.

It is not always clear how fatigue studies should be performed, and what can kind of understanding can be garnered from these evaluations. The objective of this article is to convey the significance of fatigue to the success of restorative dentistry through some examples, with emphasis on the methods for evaluating the fatigue properties of materials and their bonded interfaces, as well as the concept of durability.

2. Background

There are many aspects of fatigue failures that are unique from those caused by static loading. The first and most important characteristic of fatigue is that failures occur at stresses that are generally much lower than the static “strength” as defined by a yield or ultimate strength. As such, cyclic loading facilitates failures that are not adequately predicted by measures of static strength. Secondly, fatigue is a stochastic process that is dependent on the growth and coalescence of intrinsic flaws in the material. That indicates that the fatigue strength is not deterministic because the mechanical response is largely dependent on conditions or processes that influence the internal flaw distribution and flaw sizes. Through the energetics of the cyclic loading process, the flaws grow to a size that reduces the ability to bear load. The third quality is that fatigue of a structure is more sensitive to changes in the surface quality than other aspects of mechanical behavior. And the fourth aspect of importance is that the fatigue resistance of a material is more likely to be influenced by other contributing forms of degradation (synergistic effects). For example, corrosion of metals is a well-known surface phenomenon that can reduce the fatigue strength and together they operate to accelerate the process of degradation [26].

The special qualities of fatigue are highly relevant to the success of restorations. Cutting of the preparation and the additional steps including etching, application of a primer, etc. contribute to both the surface quality and surface integrity of the materials serving as the foundation for adhesive bonds. In addition, the structure of these bonds is complex. Bonding to dentin and enamel involves at least three distinct materials, including the restoration, the resin adhesive and the hard tissue, as well as the interfaces between them. The difficulties realized in the placement and potential curing of the restorative materials increases the likelihood of introducing defects and their average size. Depending on the preparation and the mechanisms enrolled in anchoring the restoration, there are hybrid layers and interdiffusion zones with their own unique microstructure and properties. Consequently, the fatigue strength of the adhesive bond is controlled by all of these contributing elements. Identifying the weakest link is critical to the design and development of improved materials and practices that will extend the longevity of restorations.

Considering that the magnitude of cyclic stress borne by the forces of mastication are small enough to avoid bulk fracture, then there are two potential modes of fatigue failure. The first

mode is where failure originates from existing inherent defects in the material (Fig. 1a). These defects coalesce with cyclic loading and facilitate fracture through a reduction in capacity to bear load. This process is regarded as “stress-life fatigue” and is the most common mode of fatigue. Alternatively, fatigue failures can originate from a well-defined flaw or crack (Fig. 1b) that undergoes extension via cyclic loading until it reaches a length that permits fracture due to the magnitude of the stress intensity. This process is regarded as fatigue crack growth. Both of these modes of fatigue are relevant to dental materials and the practice of restorative dentistry. Contact fatigue [27] and dynamic fatigue (or slow crack growth) [28] are also important, primarily relevant to crown materials, and warrant separate treatments.

2.1. Stress-life fatigue

The stress-life fatigue behavior of a material is evaluated by subjecting specimens with well-defined geometry to cyclic loads that result in a desired magnitude of cyclic stress. While standards are widely available that guide the choice of specimen geometry and size for most engineered materials, there are limited testing standards for dental materials. Cyclic loading of the specimens is conducted via tension or flexure at an acceptable frequency, and the number of cycles to failure is documented. Flexure is often preferred as it generates a simple stress state and reduces the problems associated with gripping and alignment of specimens that is associated with tensile loading.

If the goal of fatigue testing is to understand the average stress that results in a specific finite “life”, e.g. 50k cycles to failure, then the applied load is adjusted in subsequent tests according to the staircase method [29] to distinguish the corresponding stress amplitude that results in the life of question. However, if the goal is to understand the fatigue strength distribution over a range in potential service stress, then a fatigue life diagram is developed. Fatigue life diagrams describing the fatigue strength distribution of human coronal dentin for two donor age groups are shown in Fig. 2a. One benefit of constructing the fatigue life diagram is that the data can be modeled with a simple power law model (Fig. 2a), which describes the fatigue strength distribution over the entire range of finite life. The diagram also helps distinguish if the material exhibits a fatigue limit (S_e , also termed endurance limit), which is the cyclic stress amplitude below which the material exhibits a tremendously long life (does not fail).

Considering that the average number of masticatory cycles ranges between one and two thousand per day [30], the fatigue life diagram and determination of the endurance limit should be customary for dental materials, despite requiring a greater investment of time. For example, in comparing the fatigue strength distributions of young and old dentin in Fig. 2a, a comparison at a life of 1k cycles shows that the fatigue strength of the old dentin is roughly 25% less than that of young dentin. That comparison can be performed for any finite life, and as evident from the distribution in Fig. 2a, the relative fatigue strength of old dentin decreases with longer definition of life. A comparison of the fatigue limits (S_e) indicates that the fatigue strength of old dentin is nearly 50% lower than that of young dentin [31]. If the goal of restorative dentistry is to promote life-long oral health, then the comparisons using the endurance limit are most relevant. They are also most objective. Finite life comparisons

are valuable as well, but they provide an incomplete picture, and sometimes even misleading view, of the fatigue response.

2.2. Fatigue crack growth

The fatigue crack growth resistance of a material is determined by subjecting specimens with well-defined geometry and a sharp crack to cyclic loads that results in incremental crack extension. There are no testing standards explicitly for dental materials that guide the choice of specimen geometry and size to use for fatigue crack growth evaluations. A number of different specimens have been used for this purpose [32]. Fatigue crack growth evaluations on dental materials are often conducted using beams loaded in flexure [e.g. 33,34] or Compact Tension (CT) specimens [e.g. 18,35,36], to generate cyclic tensile stresses that achieve an adequate stress intensity range for cyclic extension of the crack. Cyclic loading of the specimens is conducted at an acceptable frequency and the crack length is measured after specific intervals of loading. The history of crack extension is then evaluated using a fatigue crack growth diagram, where the average growth rate (a/N) is plotted in terms of the average stress intensity range (K) over the increments of cyclic extension.

Similar to the comparison of fatigue strength distributions in Fig. 2a, a fatigue crack growth diagram for young and old dentin human coronal dentin is shown in Fig. 2b. This data was obtained for cyclic crack growth perpendicular to the dentin tubules [37]; the definition of the two age groups is consistent with that used for the stress-life responses (Fig. 2a). The cyclic crack growth history within a single specimen of young coronal dentin (Young*) is highlighted to enable observation of how cyclic crack extension progresses. Although the growth response of each specimen can be quantified in terms of the classical initiation and steady-state growth behavior [38], they are not really necessary to show the utility of this approach. Details of quantitative treatments applied to biomaterials are available elsewhere [22,39,40].

The fatigue crack growth diagram in Fig. 2b presents the responses for specimens obtained from the teeth of many young and old donors. The distribution of this experimental data shows that even within the young and old age groups that there is considerable variation in the responses. This variation is largely related to the spatial variations in microstructure of coronal dentin [41]. Fatigue life diagrams are useful as they enable simple comparisons of fatigue crack growth resistance. Responses to the lower right in this diagram signify a material with higher resistance to fatigue crack growth, while those to the upper left undergo fatigue crack growth more easily, as highlighted with “+” and “-” symbols in Fig. 2b. It is clear from this general description that old dentin exhibits substantially lower fatigue crack growth resistance than that of young dentin. It is also evident that the initiation of fatigue crack growth from existing cracks starts at much lower stress intensity range in old dentin. A comparison of the average growth rates can be made as a function of the stress intensity range. Choosing a value of K that is within the range of that generated by cyclic mastication [42], it is possible to compare the average steady-state cyclic crack growth rates, which is shown in Fig. 2b for $K \approx 0.75 \text{ MPa}\cdot\text{m}^{0.5}$. The ratio of the cyclic growth rates at this level of stress intensity for old and young dentin exceeds 100, indicating that cracks in

old dentin grow at 100 times the rate of those in young tissue. According to the reciprocal of this value, the corresponding “life” of old teeth with cracks subjected to the same level of mastication would be less than 1% of the life of a young tooth. This simple comparison shows that substantial degradation that can occur from the introduction of cracks within teeth during restorative processes, and that this damage is much more detrimental with increasing patient age.

2.3. Some relevant examples

With this basic understanding of how to test and characterize the fatigue and fatigue crack growth behavior of materials, it is possible to address some factors relevant to dental practice. The first concern is the importance of introducing the cavity preparation and surface quality. As previously highlighted, fatigue responses are sensitive to the surface quality of materials. Finishing of the margins and polishing of the occlusal surface are considered important steps in the placement of direct restorations. But are these steps really important to the strength and longevity of the restoration?

Lohbauer et al. [43] reported that surface texture is important to the strength of resin composites and glass ceramics, even under monotonic loading. For surfaces with average roughness (Ra) larger than 2.1 μm , flaws created by the surface treatments were large enough to have a significant effect on the strength. In regards to cutting the cavity, Staninec et al. [44] showed that laser preparations introduced cracks in dentin that exceeded 100 μm in length under some treatment conditions and caused a significant reduction in strength. But the static strength of a material is generally less sensitive to surface condition than the fatigue strength. Indeed, Majd et al. [45] reported that while there was no influence of burs or airjet surface treatments on the strength of dentin under quasi-static loading, both preparations caused significant reductions to the fatigue strength.

Cutting the preparation and etching are integral steps in the placement of resin composite restorations. Lee et al. [46] evaluated the effects of cutting and etching on both the static and fatigue strengths of coronal dentin. The average flexure strength of coronal dentin specimens prepared using diamond abrasive slicing equipment (control) was 154 ± 24 MPa. It was found that there was no difference ($p > 0.05$) in the strength between these “flaw-free” controls and specimens prepared using bur treatment or etching treatments. Hence, there were no effects of bur cutting or etching to the static strength of dentin.

A comparison of the fatigue life distribution for the control specimens (prepared by diamond abrasive slicing) with specimens that were prepared using the bur treatment (BT) is shown in Fig. 3a. Similar to the fatigue life diagram in Fig. 2a, data points represent the fatigue response of one specimen and data points with arrows represent those that did not fail within a prescribed number of cycles and the experiment was discontinued. Note that the control data is the same as that presented for young dentin in Fig. 2a, with the addition of a few more points. A similar comparison of results for the flaw free control with specimens subjected to bur treatment and followed by etching with 37.5% gel for 15 s is shown in Fig. 3b. Power law equations for the mean fatigue responses are presented in each diagram, along with the coefficient of determination (R^2) indicating the goodness of fit. According to the Mann Whitney U test, the fatigue strength of the treated control specimens receiving BT (Z

= -5.6; $p = 0.0001$) and BT + ET ($Z = -5.5$; $p = 0.0001$) treatments were significantly lower than the flaw free control. However, there was no significant difference between the responses of the BT and the BT + ET groups ($p > 0.05$). The cutting and etching treatments increased the R_a from that resulting from the diamond slicing ($0.2 \mu\text{m}$) by nearly five times ($\approx 1 \mu\text{m}$). Although this increase had no effect on the static strength, the reductions in fatigue strength exceeded to 30%.

The distributions in Fig. 3 highlight the additional value of using fatigue life diagrams to compare the resistance to fatigue failure. Not only do the BT and BT + ET treatments cause a significant reduction in fatigue strength, they also decrease the consistency in the fatigue life. The variability in fatigue data and relatively poor R^2 values of the power laws for the BT and BT + ET groups indicate that the experimental responses do not conform well to the average response defined by the power law models. This variation in fatigue strength is due to the flaws introduced at the surface during the cutting. As evident from the fatigue life distributions in Fig. 3, the flaws caused by bur cutting were most severe and relatively inconsistent among the treated specimens. Clearly the fatigue strength of dentin is decreased by surface flaws that are introduced during the cavity preparation.

There are many challenges in the oral environment that may contribute to the fatigue behavior of dental materials and the hard tissue foundation. The acid production of biofilms results in the formation of secondary caries at the bonded interface between dentin and restorative materials, and serves as one of the primary causes of restored tooth failure [6,7,47]. Yet, the potential synergism in fatigue caused by simultaneous cyclic loading and exposure to acidic conditions has received limited attention. Do et al. [48] explored the influence of a reduction in pH from neutral ($\text{pH} = 7$) to lactic acidic ($\text{pH} = 5$) conditions to the fatigue properties of coronal dentin. The exposure to acidic conditions caused a significant reduction to the fatigue strength, as expected. The most interesting aspect of the investigation is that it was identified that a significant degradation to the fatigue strength developed after only 10 h of exposure to the acidic condition. The primary mechanism of degradation appeared to be subsurface porosity caused by demineralization, which results in loss of stiffness and corresponding increase in localized surface strains, which accelerate the process of fatigue.

Changes to the microstructure of dentin caused by the acidic sections of biofilms and localized demineralization could degrade the mechanisms of toughening that are key to the fatigue crack growth resistance. That would reduce the durability of the tissue foundation supporting the restoration. Orrego et al. [49] recently explored the influence of lactic acid exposure ($\text{pH} = 5$) on the fatigue crack growth resistance of human dentin for cracks extending within the mid-coronal regions. A comparison of the fatigue crack growth responses for mid-coronal dentin evaluated in the neutral and acid environments is shown in Fig. 4a. As denoted from the shift of the fatigue crack growth responses to the upper left region of the diagram, the lactic acid environment caused a reduction in the fatigue crack growth resistance. The rate of cyclic crack extension for tissue exposed to the acidic solution is significantly greater ($Z = -6.4665$, $p = 0.0005$) than that within the neutral environment. Admittedly, there is limited influence of the environment on the stress intensity range necessary for initiation of cyclic crack extension. But when the two distributions are

compared in terms of the rate of cyclic extension, the incremental growth rate increased by over a factor of 10 in the acidic condition. That corresponds to a reduction in the apparent fatigue life by a factor of 10!

The penetration of adhesive resins within the tubules and formation of tags could be envisioned as a form of reinforcement that also resists acid from penetrating within the lumens to access the crack. The importance of resin-adhesive penetration within the lumens on the fatigue crack growth response of mid-coronal dentin has also been explored. A comparison of the fatigue crack growth responses for dentin with open lumens and for dentin with lumens sealed with resin adhesive (Ultradent Products Inc., Peak Universal Bond) is shown in Fig. 3b; both were subjected to acid exposure (pH = 5). As evident from the comparison of data in this fatigue life diagram, sealing the lumens with resin adhesive did not affect the rate of cyclic crack growth significantly ($Z = 0.4832$, $p = 0.629$). Therefore, the movement of acid buffers within the lumens and/or sealing the lumens are not important to cyclic crack extension in dentin. The fatigue crack growth resistance is degraded under acidic conditions due to the exposure of acid within the open crack and its degradation of the principal mechanisms of toughening [49]. Therefore, the exposure of dentin to acidic environments contributes to the development of caries, but it also increases the chance of tooth fractures via accelerated cyclic crack growth, and at lower mastication forces.

3. Fatigue of bonded interfaces

The microtensile and microshear techniques have served the dental materials community as the primary methods for evaluating the bonded interface strength for over 2 decades [50,51]. There are recognized shortcomings to these methods (e.g. [52–54]). One concern is that the cyclic stresses transmitted across the bonded interface are considered to be a contributing factor to its degradation over time [55,56]. Of course, the bonded interface resistance to fatigue is not necessarily represented by measures of quasi-static strength. With this in mind, there have been recommendations for the development of new test methods [57,58] that better represent oral challenges.

Studies on the fatigue strength of tooth-resin bonds are not new, with early reports on this topic appearing in the mid 90's. But while fatigue testing of the interface could provide clinically relevant insight on dentin-bond performance, relatively few studies have been reported in this area overall [61-70]. In fact, more evaluations concerning microtensile testing are published in one year than have been reported on the fatigue properties of the resin-dentin bonded interface in total. Modeling the fatigue behavior of the resin-dentin adhesive interface the finite element method is an option [71]. However, development of the model requires a number of assumptions regarding the fatigue behavior and it is difficult to capture many of the technique-sensitive aspects of the bonded interface.

We have proposed using the Twin Bonded Interface (TBI) specimen for evaluating the stress-life fatigue behavior of the bonded interface [69]. This approach utilizes a beam subjected to pure-bending under 4-point flexural loading. One unique quality is that the beam is prepared with two (i.e. twin) bonded interfaces, which are both subjected to the

same magnitude of bending stress via the flexural loading arrangement. As a result of cyclic loading, the interface with greatest number of defects undergoes fatigue failure. The second interface, which was subjected to exactly the same extent of cyclic loading, remains unbroken. It enables an evaluation of the mechanisms contributing to failure. This approach to evaluating the fatigue resistance of bonded interfaces has been used for the evaluation of adhesive bonds to both dentin [69,70] and enamel [72].

For the purpose of this review, it appears useful to describe the application of the TBI approach that builds on the methods described in Section 2. An experimental evaluation of the stress-life fatigue behavior of dentin bonds prepared with two- and three-step adhesive systems was recently conducted using the TBI approach [73]. Specimens were prepared using a selected three-step (Scotchbond Multipurpose, SBMP, 3M ESPE) and two-step (Single Bond, SB, 3M ESPE) etch-and-rinse adhesives, as well as a compatible resin composite (Z100, 3M ESPE). The beams were subjected to 4-point flexure to failure at 5 Hz within a Hanks Balance Salt Solution (HBSS) at room temperature. The stress-life fatigue diagrams were developed from results of the bonded interfaces for both adhesive systems, as well as for coronal dentin and the resin composite. Additional details of the experimental methods have been presented previously [73].

A comparison of the fatigue strength distributions for the resin-dentin bonded interfaces prepared with SB and SBMP adhesives is shown in Fig. 5a. Results are also shown from the experiments performed on the Z100 and coronal dentin in this figure for comparison. Basquin-type power law models are used to outline the mean of each fatigue strength distribution. Not surprising, the fatigue strength distributions for the bonded interfaces are significantly lower than those for Z100 and coronal dentin. The results also show that the bonded interfaces prepared with SBMP adhesive exhibited significantly greater fatigue strength ($Z = -3.45$; $p = 0.001$) than those prepared with SB. The power law models developed for each of the distributions were used to estimate an apparent endurance limit for each of the bonded interface systems at 1×10^7 cycles. According to this approach, the apparent endurance limit for the SB and SBMP interfaces were 8.4 MPa and 14.4 MPa, respectively. These values are between only 20–30% of those values for the Z100 control (42 MPa) and dentin (43 MPa). Cyclic loading is clearly detrimental to the bonded interface.

A complementary assessment of static and fatigue strength is considered useful in evaluating the mechanical behavior of bonded interfaces [68]. It is worthwhile to highlight the importance of that statement here. The apparent endurance limit of the SBMP bonded interface was over 70% greater than that achieved by SB. However, a complimentary evaluation of the strength of the bonded interfaces for these two adhesives under quasi-static loading showed that there was no significant difference in the flexure strength [73]. The ratio of the fatigue limit to the quasi-static strength for the interfaces prepared with SBMP and SB was approximately 0.37 and 0.3, respectively. As previously indicated, the results of static evaluations are not a reliable indication of the fatigue performance of materials, and this also applies to the bonded interface.

If flaws are located at the bonded interface including within the resin adhesive, the hybrid layer or the additional interfaces involving the resin composite and dentin, then the

“initiation” phase of the fatigue life is relatively short. In these instances, the bonded interface durability will be related to its resistance to the “propagation” of these defects via cyclic extension. Soappman et al. [65] proposed a method for evaluating the fatigue crack growth resistance of resin-dentin bonds based on conventional fracture mechanics. This approach utilizes a Compact Tension (CT) specimen that is developed with a bonded interface between dentin and resin-composite. It is then subjected to cyclic loading as described in Section 2.2 within a hydrated environment to promote cyclic crack growth along the bonded interface.

Similar to the comparison of the fatigue behavior of the bonded interfaces prepared as shown in Fig. 5a, the fatigue crack growth responses for the interfaces are shown in Fig. 5b. These results are presented along with those obtained for the resin composite and coronal dentin. Interestingly, there is no significant difference ($p > 0.05$) in the fatigue crack growth responses between the Z100 and dentin. The fatigue crack growth resistance of the bonded interfaces is significantly lower than that of the dentin and resin composite. The bonded interfaces prepared with SB adhesive exhibit significantly greater resistance to fatigue crack growth than that obtained with SBMP. The interfaces prepared with SB required significantly lower stress intensity range (K) to enable incremental fatigue crack growth to occur. In addition, the average incremental crack growth rate for the SBMP interface is approximately 10 times greater than that for SB at equivalent values of driving force (i.e. K).

It is interesting that results from the fatigue crack growth analysis contradict those of the stress-life fatigue responses, as well as the results from the quasi-static loading experiments. Each of these forms of loading address a unique component of the mechanical behavior. The bonded interfaces prepared with the three-step resin adhesive (SBMP) exhibited higher stress-life fatigue strength, but lower resistance to fatigue crack growth. According to a microscopic evaluation of the fracture surfaces, both interfaces failed within the hybrid layer. However, the SBMP had a poorer degree of integration within the dentin matrix. While both adhesives exhibited good penetration into dentinal tubules and well-developed resin tags, the fractured tags were often displaced above or below the fracture surface proper in the SBMP. That implies that the SBMP suffered from a lower degree of hybridization between the fibrils and adhesive. Many of the resin tags appeared to be dislodged from their foundation by the cyclic loading process. Evidence of this form of degradation was not seen for the SB. Therefore, while the SB exhibits inferior resistance to fatigue, it has greater damage tolerance as evident from the superior resistance to fatigue crack growth.

4. Durability

There are many more threats to the life of resin-dentin adhesive bonds than mechanical fatigue as a result of cyclic loading. Of course, degradation by the acidic secretions of oral biofilms [74,75] and the degradation of dentin collagen within the hybrid layer by endogenous Matrix Metalloproteinases (MMP) [76,77] are considered amongst the most critical. These forms of degradation can undergo a synergism that accelerates the damage that causes failure. Here we use the term “durability” to describe the resistance of resin-dentin adhesive bonds to failure under the combined effects of mechanical fatigue and these

additional sources of degradation. The following sections describe the results of experimental studies that address this concept.

4.1. Biofilm attack

Degradation of the bonded interface due to biofilm attack is an important concern. Resin composites accumulate more biofilm/plaque than other restorative materials [78]. Biofilms cause an increase in the surface roughness of resin composites [79], which also facilitates the adhesion of bacteria [80]. This increase in surface roughness further encourages biofilm formation [81]. Surface characteristics are important to the fatigue response. Microleakage permitted by inter-facial degradation or fatigue-related damage could enable bacteria to invade the interface and promote the development of caries and/or accelerate mechanical failures. Indeed, Khovostenko et al. [82] showed that cyclic loading promoted an increase in the depth of marginal gaps and corresponding bacterial penetration in comparison to bonded interfaces not subjected to cyclic loading. Marginal gaps can serve as critical defects that enable cyclic crack growth from the gap root. There is evidence that calcium phosphate and bioactive glass fillers could suppress biofilm activity [83] and the development and penetration of marginal gaps [84]. Prior to development of these gaps, or if their growth can be limited, the stress-life fatigue behavior of the bonded interface will be important.

One approach to evaluating the interface durability is to consider the biofilm and the fatigue portions separately, or sequentially. This approach was used in the study of Mutluay et al. [70], which was performed to evaluate the degradation in fatigue properties of resin–dentin bonded interfaces caused by exposure to a biofilm of *Streptococcus mutans*. In this particular investigation, the TBI specimen configuration was used. The specimens consisted of sections of mid-coronal dentin and a commercial resin composite (Clearfil AP-X, Kuraray America, Houston, TX, USA) resin composite. The bonded interfaces were prepared using a compatible primer and adhesive (Clearfil SE Bond) according to the manufacturer's recommendations.

The biofilm treatment involved exposing the molded specimens to *S. mutans* bacteria according to a protocol approved by the University of Maryland Baltimore. The specimens were placed in separate wells of a 24-wellplate, inoculated, and incubated at 5% CO₂ and 37 °C for 14 days to simulate the demineralized caries-affected dentin [85–88]. The inoculation medium was supplemented with a growth medium of 0.2% (v/v) concentration sucrose after McBain [89], and changed once every 24 h over the 14 day exposure period. Additional details of the inoculation medium were detailed previously. An additional group was subjected to deionized (DI) water exposure (without biofilm) at room temperature (22 °C) for 14 days. The control group of bonded interface specimens was stored in DI water for one day (i.e. 24 h). After completing the respective durations of exposure, the specimens were subjected to 4-pt flexure under quasi-static or cyclic loading to failure.

Fatigue life diagrams obtained from cyclic loading of the specimens are shown in Fig. 6a. Power law models indicating the mean fatigue life distributions for each group are shown to help in the comparison. The fatigue life distributions for water aging one and 14 days were not significantly different ($Z = -0.08$; $p = 0.468$). However, the fatigue strength of the specimens exposed to biofilm for 14 days was significantly lower than that after water aging

($Z = -3.11$; $p = 0.001$), regardless of the period of storage. Using the parameters obtained for the power law models, the apparent endurance limits were defined at 1×10^7 cycles. The apparent endurance limit for the interface after water aging for one and 14 days was 13.0 MPa and 13.1 MPa, respectively. For the specimens exposed to biofilm that value was 9.9 MPa (nearly 25% lower). Fatigue failure of the specimens stored in water initiated within the resin composite adjacent to the interface. However, failure of the specimens subjected to the biofilm challenge initiated within the hybrid layer and appeared to be attributed to the localized demineralization of dentin.

An important concern in evaluating the bonded interface durability is the rate of degradation associated with each challenge. Mechanical fatigue of dentin occurs as a function of the stress amplitude and the accumulation of loading cycles. The degradation associated with biofilm exposure is potentially more dependent on time, and the growth environment. In the development of protocols for evaluating interface durability with combined challenges, it is important to consider the relative impact of the chosen conditions. As an example, a recent experimental study was performed that considered the influence of cariogenic protocols on the degradation in fatigue strength of dentin [90]. Two groups of samples were tested using a dynamic biofilm-fatigue simulator under simultaneous biofilm attack and cycling loading. In the first group the inoculation medium was supplemented with sucrose with 0.2% (v/v) concentration after McBain [89] and the medium was replaced once per day. In the second group the medium was supplemented with 2.0% (v/v) concentration [83,91] and replaced twice a day. A group of control specimens was exposed to the same cycling loading conditions but without the biofilm attack. For this group an HBSS bath ($pH = 7$) was used during testing to maintain mineralization and hydration at neutral pH. Details concerning the dedicated biofilm-fatigue simulator and the remaining conditions of evaluation were described previously [90].

Fig. 6b compares the fatigue life distributions for dentin specimens exposed to biofilm in comparison to the control environment ($pH = 7$). Each data point corresponds to failure of a single beam. Those points with arrows represent beams that did not fail and the test was discontinued. For the 0.2% sucrose supplement pulsed once per day, there was no apparent difference in the fatigue response from the control. In contrast, the biofilm model with 2.0% sucrose pulsed two times per day caused a significant reduction in the fatigue strength ($p < 0.001$). The apparent endurance limit defined at 1.2 M cycles for the dentin specimens with biofilm challenge of 2.0% sucrose pulse was 20 MPa. That value is approximately 60% lower than for the control (50 MPa) at the same definition of fatigue limit.

The difference in apparent endurance limit between the biofilm supplemented with 0.2% and 2.0% sucrose concentrations highlights the importance of the testing protocol to the apparent interface durability. This will be an important concern in comparing the results of future studies that pursue an evaluation of dentin bond durability involving biofilm exposure. Due to the importance of this factor, it appears prudent to consider the development of standards, or guidelines at the very least, for fatigue testing of the bonded interface that are focused on this aspect of durability.

4.2. Enzymatic degradation

Adhesive bonds to dentin undergo a gradual reduction in durability over time [55,92,93]. Apart from the degradation by oral biofilms, one of the primary threats to resin-dentin adhesive bonds is the exposure to, and activation of, endogenous dentin proteases [92,94]. Contemporary bonding procedures involving either etch-and-rinse or self-etch adhesives cause activation of matrix-metalloproteinases (MMP)s and cysteine cathepsins [77,95–97]. These host-derived proteolytic enzymes are bound to the dentin collagen matrix. When uncovered by etching the MMPs slowly solubilize the collagen fibrils [94], which triggers the gradual destruction of poorly infiltrated fibrils within the hybrid layers [56,98,99]. The reduction in collagen integrity can weaken anchored resin tags that serve as weak links of the bonded interface [73]. The degradation of collagen resulting from endogenous protease activity can cause a decrease in bond strength over time and reduce the durability.

Various cross-linking agents have been explored as a treatment that follows etching to resist the activation of dentin proteases [100–102]. Carbodiimide has appeared most recently as one of the most promising cross-linkers for stabilizing dentin bonds. It has comparatively low cytotoxicity, and an ability to preserve dentin bond strength within clinically acceptable treatment times [103–106]. Yet, we have seen that results from quasi-static tests are not necessarily consistent with the fatigue response.

The degradation in dentin bond durability resulting from dentin proteases and the effectiveness of an EDC treatment in stabilizing the fatigue response were recently explored by Zhang et al. [73,107,108]. The experimental evaluation consisted of evaluations of the stress-life fatigue behavior and the fatigue crack growth resistance. Specimens with the TBI and CT configurations were prepared as discussed earlier using sections of coronal dentin and the necessary molding techniques (Section 3). Adhesive bonding was performed with a commercial three-step resin adhesive (Scotchbond Multipurpose, SBMP, 3M ESPE) according to the manufacturers recommendations. The dentin was etched for 15 s (SB 37% phosphoric etchant) and rinsed with water in preparation for bonding. Then the SBMP primer and adhesive were applied to the etched surface according to the manufacturer's recommendations. For the treated specimens, the application of primer and adhesive was preceded by conditioning the demineralized collagen using an experimental solution of 0.5 M ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC) for 60 s. The specimens were completed using a compatible resin composite (Z100, 3M ESPE). Details regarding the bonding and molding process have been presented earlier. Control specimens for both configurations of testing were prepared without the EDC treatment.

The fatigue strength and the fatigue crack growth resistance of the specimens was evaluated after a storage period of 0, 3 or 6 months. Those specimens evaluated at 0 months (i.e. without storage) are considered to represent the “immediate” fatigue crack growth resistance and were tested after a period of at least 48 h from the date of preparation.

The stress-life fatigue responses for the resin-dentin bonded interface samples prepared without EDC treatment (i.e. controls) and evaluated after 0, 3 and 6 months of storage is shown in Fig. 7a. As evident from the distribution of the data, there is a significant reduction ($p < 0.05$) in the fatigue strength after the 3 and 6 month storage periods with respect to that

immediately after bonding. Also apparent from the distributions in fatigue strength, it is difficult (or even not possible) to quantify a fatigue limit; there is no apparent increase in fatigue life with a decrease in magnitude of cyclic stress. This behavior is relatively atypical, and is the result of defects existing at the interface, and the contribution of degradation that occurs as a function of storage. These defects serve as the seeds to fatigue failure under cyclic loading. As such, the fatigue life of each sample is a large function of the severity of the intrinsic defects as well as the degradation by dentin endogeneous proteases. Storage enables the activation of dentin protease and a decrease in fatigue strength. After 6 months of storage the fatigue strength is reduced by over 30% with respect to that shortly after bonding.

The fatigue crack growth responses obtained for the samples prepared without EDC treatment is shown in Fig. 7b as a function of the three periods of storage. As evident in this diagram, there is a translation in data to the left with increasing period of storage, which signifies a reduction of the fatigue crack growth resistance. Indeed, the fatigue crack growth resistance of the control groups evaluated after 6 months was significantly lower than that for the group evaluated immediately after dentin bonding ($Z = -4.71$; $p < 0.0001$).

A comparison of the fatigue crack growth responses for the control and EDC treated bonded interface specimens after 6 months aging is presented in Fig. 8a. There appears is a transition of the data for the control specimens to the left with increasing storage time. The EDC-treated group exhibited significantly greater resistance to fatigue crack growth than the control group after 6 months storage ($Z = -3.95$; $p < 0.0001$). A statistical comparison of the fatigue crack growth responses for the EDC treatment specimens showed that with the 6 months of storage there was no significant decrease in the fatigue crack growth resistance ($Z = -.30$; $p = 0.19$) [107]. Similar results have been obtained for the stress-life fatigue responses.

It is generally valuable to complement quantitative evaluations of the fatigue response with a characterization of the fracture surfaces and the underlying microstructure. To many in this field this is a mandatory part of their investigation and essential for understanding the mechanisms of failure. Fig. 8b presents additional high magnification views of the fracture surfaces resulting from fatigue crack growth in the control specimens that were evaluated after 6 months storage. This micrograph provides details the interface between the resin tags and interpenetrating collagen fibrils. There are sparse collagen fibrils extending across the interface of the intertubular matrix to the penetrating tags. This suggests that all other collagen fibrils that anchored the resin tags had dissolved. Some of the residual fibrils are still apparent, an appear degraded as evident from the reduction in diameter (white arrows). There are also fractured fibrils at the boundary of the tags caused by fatigue. A high magnification view of the bonded interface of a control specimen evaluated via transmission electron microscopy after fatigue crack growth is shown in Fig. 8c. Note the extensive degradation of the top 20% of the hybrid layer. Empty voids filled with embedding epoxy resin indicate the complete degradation of collagen fibrils. Some fibrils are much thinner than normal, indicating protease degradation. This degradation was not evident in the EDC treated specimens [107,108].

The average rate of cyclic crack extension in the control group bonded with SBMP was between one to eight times higher than in the EDC treated group after 6 months of storage! Thus, results of the fatigue crack growth evaluation indicate that the EDC treatment improved the durability of the dentin bonds. In Mazzoni *et al.* [105] the treatment of etched dentin for 1 min using a 0.3M EDC solution resulted in roughly 25–35% higher bond strengths after 12 months of water storage. Comparing these studies suggests that the fatigue crack growth resistance of resin-dentin adhesive bonds is more sensitive to degradation than the microtensile strength. That is expected due to the importance of collagen fibril reinforcement to the fatigue crack growth resistance [73]. Collagen fibrils are essential elements of the toughening mechanisms that resist crack growth in dentin bonds. Degradation of the reinforcing collagen fibrils severely diminishes these mechanisms of toughening.

There are a number of limitations to the aforementioned studies concerning the durability of dentin bonds. For example, the relatively short time periods of exposure to the biofilm and water storage and the lack of cyclic loading in the evaluation concerning dentin proteases are two of the most immediate concern. There are others related to the cyclic loading frequency and aspects of the fatigue cycle that are important as well. Nevertheless, these shortcomings provide motivation for developing improved methods of evaluation that more closely simulate the challenges of the oral environment.

5. Summary

The cyclic nature of chewing and the failure of restorations after prolonged periods of oral function are indications of the relevance of fatigue to the practice of restorative dentistry. The dental materials community has not yet adopted fatigue testing as one of the principal methods for evaluating the potential clinical success of new restorative materials and the complimentary approaches used for their placement. Fatigue failure can occur within the hard tissue foundation, the restorative and/or the bonded interface. Depending on the distribution and size of intrinsic flaws within each of these materials, failure can occur as a result of conventional stress-life fatigue or fatigue crack growth. In this manuscript a description of these two modes of fatigue failure was presented, along with methods of testing and examples of their application to understanding fatigue of dentin, the restorative materials and the resin-dentin bonded interface. Studies reported on the fatigue behavior of dentin and the interface show that flaws introduced during the restorative process result in a significant reduction of the fatigue strength. Similarly, the exposure to localized reductions in pH can reduce the fatigue strength and fatigue crack growth resistance of both the hard tissue foundation and the bonded interface. New approaches have recently been developed for evaluating the durability of the bonded interface, which consider fatigue failures promoted by the synergistic degradation of cyclic loading with biofilm attack, and cyclic loading after activation of endogenous dentin proteases.

The application of these approaches is just the beginning, and will hopefully foster the development of a more realistic understanding of fatigue failures in the oral environment. Further refinements in the methods, and a growing emphasis on the importance of their

application, will be essential to solving some of the critical issues that limit the success of restorative dentistry.

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Fig. 1. Schematic description of a material subjected to a cyclic stress (S) that has (a) small randomly distributed intrinsic defects, and (b) small intrinsic defects and a well-defined flaw. In the case of (b), the larger defect could develop through growth of the smaller defects in response to cyclic loading into one of larger size, or as a result of steps involved in the restoration process that cause a larger flaw.

Fig. 2.

Characterizing the fatigue behavior of dentin and importance of age using two different approaches. The tissue used in these studies was coronal dentin from 3rd molars and the two age groups are defined as young (age 35) and old (55 age). (a) A comparison of the fatigue life diagrams for dentin within the two age groups. Data points represent beams that failed and data points with arrows indicate testing that was stopped after roughly 1.2 million cycles because the specimen did not fail. Basquin-type power law models are presented, which defines the mean fatigue strength over the entire fatigue life distribution. The apparent fatigue limit (S_e) is also highlighted, which defines the cyclic stress amplitude below which fatigue failure does not occur. (b) A comparison of the fatigue crack growth resistance for dentin within the two age groups. This data is obtained from multiple specimens, and each data point represents a measurement of the average incremental growth of the crack per cycle (da/dN) for a specific stress intensity range (ΔK). The (+) and (-) markers highlight regions of better and worse fatigue crack growth resistance as the top right signifies higher fatigue crack growth rates at low stress intensity range.

Fig. 3.

A comparison of fatigue life diagrams for coronal dentin after specific steps involved in the placement of a restoration. The “control” consists of dentin beams that were prepared with conventional diamond slicing equipment and that resulted in an average surface roughness of less than $0.2\ \mu\text{m}$. These specimens are considered free of flaws. (a) comparison of fatigue life distributions for the control and dentin beams subjected to bur treatment. Cutting was performed with a 6-flute tungsten carbide straight fissure bur (Model FG 57, SS White, Lakewood NJ, USA) and commercial air turbine (Midwest Quiet Air-L High Speed Handpiece, Dentsply, York, PA, USA) with water spray irrigation. (b) comparison of fatigue life distributions for the control and dentin beams subjected to bur treatment followed by a 15 s etch with 37.5% gel (Kerr). In both (a) and (b), each data point corresponds to fatigue testing and failure of a single dentin beam. Data points with arrows identify beams that did not fail and the test was discontinued. The R^2 accompanying each empirical equation of best fit represents the coefficient of determination. Note that the average flexure strength of dentin beams prepared with these three conditions (control, BT and BT + ET) was approximately 150 MPa and there was no apparent influence of the treatments. Data is from Lee et al. [46].

Fig. 4.

Fatigue crack growth responses for mid-coronal dentin (i.e. midway between the pulp and dentin-enamel junction) after being subjected to cyclic loading in either a neutral (control, pH = 7) or acidic (lactic acid solution with pH = 5) environments. These distributions are for cracks extending in-plane and perpendicular to the tubules [37]. (a) A comparison of growth rates within neutral and acidic environments. Cyclic crack growth within the acidic environments occurs at a significantly greater rate ($Z = -6.447$, $p = 0.0005$). (b) A comparison of fatigue crack growth for dentin with open lumens (Acid) and after sealing the lumens with resin adhesive (Acid + Sealed). There was no significant difference in the responses between the dentin with open and sealed lumens ($Z = 0.4832$, $p = 0.629$). Therefore, the acid attack and degree of degradation was equivalent.

Fig. 5.

A comparison of fatigue responses for the resin-dentin bonded interface. (a) Fatigue life distributions for the bonded interface specimens prepared with a commercial two-step (SB) and three-step (SBMP) resin adhesive and comparison with the distributions for dentin and the resin composite (Z100). Note that the data points with arrows represent those specimens that reached at least 1.2×10^6 cycles and the test was discontinued. (b) Fatigue crack growth distributions for the same materials evaluated in (a). As expected, the fatigue strength and fatigue crack growth resistance of the bonded interfaces are significantly lower than those of the resin composite and dentin. However, note that while the interface prepared with two-step resin adhesives shows inferior fatigue strength, it exhibit superior resistance to fatigue crack growth. Results for the interfaces are from Zhang et al. [73]. Results for dentin are for fatigue crack growth perpendicular to the tubules and were reported in Ivancik et al. [37].

Fig. 6.

(a) A comparison of the fatigue responses for the SB and SBMP interfaces with results for resin-dentin bonds prepared with SE Bond. Data is from Mutluay et al. [70]. Results for all three systems were obtained using the twin bonded interface approach. Note the value of generating the fatigue life diagram towards understanding the complete fatigue behavior of the bonded interfaces. (b) The influence of cariogenic protocols on the degradation in fatigue strength of dentin [90].

Fig. 7.

An evaluation of the fatigue properties of resin-dentin bonded interfaces prepared with a commercial three-step adhesive (SBMP). These specimens were prepared, stored in simulated saliva at 37 °C, and then evaluated after 0, 3 and 6 months. (a) reduction in the fatigue strength distribution with aging. (b) decrease in the fatigue crack growth resistance with aging. According to the Wilcoxon Sum Rank test, the reductions in fatigue strength and fatigue crack growth resistance were both significant at both the 3 and 6 month periods.

Fig. 8.

Importance of cross-linking on the fatigue crack growth resistance of resin-dentin bonded interface prepared with three-step adhesive (SBMP). (a) A comparison of the fatigue crack growth responses after 6 months aging for the control specimens (shown in Fig. 6) and specimens treated with EDC for 60 s before application of the adhesive. The fatigue crack growth rate is significantly lower in the EDC treated samples. (b) high magnification SEM view of the interface between the resin tags and interpenetrating collagen fibrils of the intertubular dentin for a control specimen after 6 months of aging. Scale bar represents 2.5 μm . Arrows are used to highlight fractured fibrils (black) and degraded fibrils (white). (c) stained, demineralized section of a CT specimen incubated in water for 6 months before crack propagation through the interface. E indicates the adhesive. This high magnification view shows large voids (asterisk) that have developed amongst the degraded collagen fibrils. Some collagen fibrils showed reduced diameter degradation (pointer). Data is from [107,108].