Chapter 13

Fracture Mechanics in Adhesive Dentistry

Mügem Aslı Gürel,

Bağdagül Helvacıoğlu Kıvanç and Hacer Deniz Arısu

Additional information is available at the end of the chapter

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Abstract

Bond strength between adhesive systems and the tooth structure is influenced by a large number of variables. The bond strength tests are important tools for improving resin-tooth adhesion to increase the service life of dental resin–based composite restorations. This chapter discusses the materials used in adhesive dentistry and test methods applied for evaluating bond strength between tooth structure and adhesive materials.

Keywords: adhesion, adhesive dentistry, bond strength, fracture strength, tooth

1. Introduction

Adhesion or bonding is the process of forming an adhesive joint, which consists of two substrates joined together [1]. Adhesives join materials together to resist separation and transmit loads across the bonds [2]. In dentistry, the adherend is the substrate to which the adhesive—enamel and dentin, rarely cementum—is applied [1]. The mechanisms of adhesion to the inorganic and organic components of teeth have relied primarily on the evaluation of morphologic relations of materials with tooth substrates [2]. In 1952, Kramer and McLean published an article about adhesion, in which altered impregnation of dentin surface, resulting from the interaction with glyrecophosphate dimethacrylate, was observed [3]. After few years, the pioneering work of Michael Buonocore marked the beginning of successful "adhesive dentistry". Buonocore's discovery of the acid-etch technique has led to major changes in recent dental practice. He showed that the treatment of enamel with phosphoric acid resulted in a porous surface, which could be infiltrated by resin material, to produce a micromechanical bond [4]. On the other hand, chemical bonding was developed by Smith and resulted in the introduction of polycarboxylate cement into the dentistry. The basic bonding mechanism was an ionic attraction between cement and enamel or dentin [5].

2. Adhesion to tooth structure

Tooth is composed of enamel, the pulp-dentin complex, and cementum (**Figure 1**). Enamel covers the anatomic crown of the tooth and varies in thickness in different areas. Enamel is composed of hydroxyapatite, organic matrix proteins, and water. Enamel has high elastic modulus, high compressive strength, low tensile strength, and supports dentin to withstand masticatory forces. Dentin and pulp tissues are specialized connective tissues. Dentin forms the largest portion of the tooth structure, extending almost the full length of the tooth. Human dentin is composed of approximately 50% inorganic material and 30% organic material by volume [6]. Dentin is considerably more complex and consists of solid and porous phases. The porous phase consists of numerous fluid-filled tubules emanating from the pulp. They transverse the dentin to the dentino-enamel junction, making dentin a highly permeable tissue. Each dentinal tubule is surrounded by a collar of hypermineralized, peritubular dentin [7]. The structure surrounding the peritubular dentin is intertubular dentin, which is approximately 9% less mineralized than peritubular dentin. The intertubular dentin is a biphasic biologic composite that contains mineral and organic components [8]. The humidity and organic nature of dentin makes bonding to this hard tissue extremely difficult [1]. Dentin has a low elastic modulus, high compressive strength, and high tensile strength and increases the fracture toughness of enamel. Externally, dentin is covered by enamel on the anatomic crown and cementum on the anatomic root. Cementum is a thin layer of hard dental tissue covering the anatomic roots of teeth. Cementum is slightly softer than dentin and consists of about 45–50% inorganic material (hydroxyapatite) and 50–55% organic matter and water by weight. Internally, dentin forms the walls of the pulp cavity (pulp chamber and pulp canals). The dental

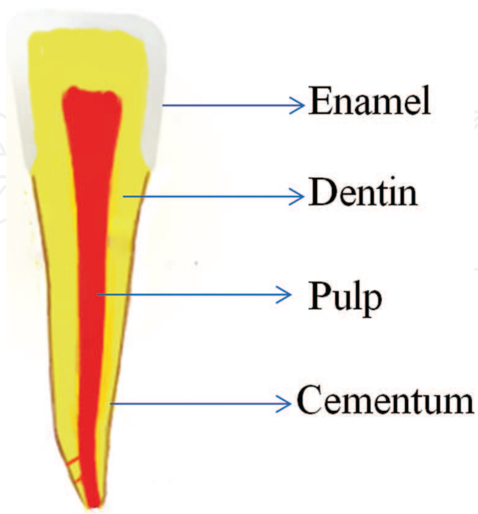

Figure 1. Structures of tooth.

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pulp occupies the pulp cavity in the tooth and is a unique, specialized organ of the human body [6]. The pulp contains nerves, arterioles, venules, capillaries, lymph channels, connective tissue cells, intercellular substance, odontoblasts, fibroblasts, macrophages, collagen, and fine fibers [9].

During the past decades, restorative concepts have been continually changing and adhesive technology has become more important. Adhesion to enamel was followed by adhesion to dentin [10]. Adhesion to tooth structure primarily depends on the displacement of inorganic tooth substrate with the resinous materials [11]. In this circumstance, there are two steps. In the first step, inorganic part of tooth (calcium, phosphate) is removed from enamel and dentin surfaces to create microporosities. In the second step, when resin materials are applied to these surfaces, they infiltrate into these microporosities and subsequently polymerized. This process is named as 'hybridization'. This is a mechanical interlocking between the tooth structure and resin material and depends primarily on the diffusion mechanism of the resin material into the microporosities of tooth structure. Although it is believed that micromechanical interlocking has a primary role on achieving a clinically good bonding, there are chemical interactions between functional monomers and tooth components that have a potential benefit on additional bond strength [12].

3. Classification of adhesive materials

3.1. Bonding agents

One of the greatest challenges in restorative dentistry is to obtain an effective seal of the tooth-restoration interface. Adhesive restoration (composite resin, etc.) rely on bonding systems that form a micromechanical bond with the tooth structure [13]. During the tooth preparation with burs or other instruments, smear layer (composed of hydroxyapatite and altered collagen) forms a coating on enamel and dentin, reducing the permeability of dentin [14]. The smear layer acts as a physical barrier against the penetration of adhesive monomers into the dentin tubules. Therefore, for adhesive penetration into dentin surface, it must be dissolved or made permeable [1]. Contemporary adhesives interact with the dental substrates using one of the two different bonding strategies in order to remove or alter smear layer: (1) the etch and rinse technique, which requires smear layer removal before the use of dentin adhesive, and (2) the self-etch technique, in which the smear layer is maintained as a substrate for bonding. In addition, these two bonding strategies may be classified according to the number of application steps (step 1 to step 3) required to couple the resin composites to dental substrates. Etch and rinse adhesives require a separate etching step. Thus, an inorganic acid (mostly 30–40% phosphoric acid) is applied to dental substrates and then rinsed off. This step is followed by a priming treatment, wherein amphiphilic functional resin monomers are applied to dental substrates to make them prone to receiving a mixture of relatively more hydrophobic resin monomers that will complete the bonding procedure. This sequence of events exemplifies a three-step application procedure. Simplified two-step etch and rinse adhesives combine the primer and adhesive resin into a single application step. On the other hand, self-etch adhesives no longer require a separate etching step. This approach requires the use of nonrinse acidic monomers that simultaneously etch and prime dentin. The bonding procedure with self-etch adhesives can be achieved using either two- or one-step systems, depending on whether the etching/primer agent is separated from the adhesive resin or combined with it to allow a single application step [15].

3.2. Glass-ionomer cements

Glass-ionomer cements were introduced to the profession 20 years ago and have been shown to be a very useful adjunct to restorative dentistry [16]. Glass-ionomer cements remain as the only materials that are self-adhesive to tooth tissue, without any surface pretreatment. Glass ionomers are composed of organic acid and glass component and set with an acid-base reaction [17]. The major advantages of glass-ionomer cements are a continuing fluoride release throughout life of the restoration and the ion exchange adhesion to both enamel and dentin. However, apparent lack of physical strength and translucency are disadvantages of glass-ionomer cements. Small additions of resin increase the physical properties to a degree and allow for a light-initiated setting mechanism [16].

3.3. Compomers

This material is a polyacrylic/polycarboxylic acid–modified composite. Polyacid-modified resin-based composites or compomers combine the characteristics of both composites and glass ionomers into a single component. It is an attempt to take advantage of the desirable qualities of both materials: the fluoride release and ease of use of the glass ionomer cement and the superior material qualities and aesthetics of the composites [18]. They contain 72% (by weight) strontium fluorosilicate glass and the average particle size is 1.5 μm [19]. The mechanical properties are superior to glass-ionomer cements as clinically demonstrated by lower fracture rates. Furthermore, wear does not seem to be critical after short-term [20].

3.4. Composite resin materials (CRMs)

CRMs are the universally used tooth-colored direct/indirect restorative materials in dentistry. CRMs were developed by combining dimethacrylates (epoxy resin and methacrylic acid) with silanized quartz powder in 1962 [21]. They have taken over some restorative materials depending on their properties and advantages. CRMs are composed of resin matrix (organic content), fillers (inorganic part), and coupling agents. Bis-GMA (bisphenol-A glycidyldimethacrylate) and TEGDMA (triethylenglycol-dimethacrylate) constitute resin matrix of CRMs. The fillers are made of quartz, ceramic, or silica. With increasing filler content, the polymerization shrinkage, the linear coefficient, and water absorption are reduced and the compressive and tensile strength, and the modulus of elasticity and wear resistance are improved [22]. The coupling agent is a molecule that connects resin and inorganic matrix of composites [23].

Choosing a suitable composite resin material for a restoration requires functional properties, including excellent mechanical properties such as high strength, fracture toughness, surface

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hardness, optimized modulus of elasticity, low wear, low water sorption and solubility, low polymerization shrinkage, low fatigue and degradation, and high radiopacity [24].

3.5. Root canal sealers

A successful root canal treatment depends on proper diagnosis, adequate cleaning, shaping, and finally, the three-dimensional (3D) obturation of the root canal system. The complete obturation of the root canal system and the creation of a fluid tight seal have been proposed as a goal for successful endodontic treatment [25]. Gutta-percha and root canal sealers are usually used for obturation of root canals. Improvements in adhesive technology directed their attention toward the characteristics of the filling material, for increasing the adhesion of the endodontic sealers to root canal walls. The adhesion between root canal walls and resin-based sealers is the result of a physicochemical interaction across the interface, enabling the union between the filling material and root canal walls [26]. Several resin-based sealers, such as AH 26, AH Plus, EndoREZ, Real Seal, and Epiphany, etc., have become available in dental markets. The aim of these resin bonding systems is to allow for the adhesion of the obturation material and to form a hermetic seal [27].

3.6. Postcore restorations and luting cements

Endodontically treated teeth are more susceptible to fracture possibly due to extensive loss of tooth structure which may be arising from extensive decays, previous large restorations, broad access cavities, aggressively flared, and overinstrumented canals [28, 29]. When a significant coronal tooth structure has been lost, a full crown may be restoration of choice. More frequently, the cementation of a post inside the root canal is necessary to provide attention for the core material and the crown. The core is anchored to the tooth by extension by the root canal through the post and replaces missing coronal structures. The crown covers the core and restores the esthetics and function of the tooth. The post's ability to anchor the core is also an important factor for successful reconstruction. Finally, luting material used to cement the post, the core, and the crown to the tooth will also influence the longevity of the restoration. The post, the core, and adhesive materials together form a foundation restoration to support the future crown [30] (**Figure 2**).

In recent years, nonmetalic posts, such as zirconia, fiber-reinforced posts, and polyethylene-woven fiber-reinforced posts, have become quite popular. Among these posts, glass fiber-reinforced posts are most popular. These posts could be made from glass or silica fibers (white or translucent) but the most commonly used fibers are silica based. The matrix for this post is an epoxy resin [31]. The clinical success of fiber-reinforced post systems is due to their presenting good retention properties under mechanical strain as a result of their low elastic modulus (17.5–21.6 GPa), which is similar to that of dentin (14.0–18.6 GPa) [32]. Therefore, by using a fiber post with a modulus of elasticity very similar to that of dentin, tooth-postcore monoblock can be achieved instead of an assembly of heterogeneous materials. This can help to distribute masticatory loads to homogenously reduce stress during function [33].

Retention is important for the use of intracanal posts in endodontically treated teeth [34]. The major factors affecting post retention are their dimensions (length, diameter), shape (conical, cylindrical), type of surface (serrated, screw, and smooth), intracanal shape preparation, type of cement, and operator skills [35].

Adhesive resin-based cements contain 4-methyacrylate-ethyl-trimethyl-anhidride that reacts chemically with the oxide metallic layer increasing post retention compared to nonadhesive resin cements [36]. The capacity of different cements to retain posts is related to mechanical properties, adhesion capacity to dentin, and durability [37]. The elastic modulus of resin cements is close to dentin and fiber post, and its stress concentration in dentin is low. Therefore, roots reinforced with posts that are cemented with dentin adhesives and resin cements are more fracture resistant than those cemented with other cements [33].

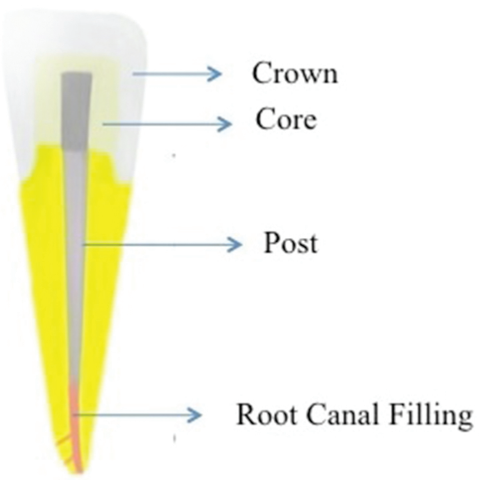

Figure 2. Schematic presentation of a postcore and crown restoration.

3.7. Ceramic crown restorations

Dental crowns are used to replace the natural crowns of teeth when the enamel and dentin are lost through dental caries, tooth wear, root canal treatment, or trauma. The aims of a dental crown are to restore function, occlusion, and contact points with adjacent teeth and aesthetics. In addition, a full coverage crown may be used to prevent further controlled loss of tooth substance by catastrophic fracture of weakened tooth cusps [38]. All ceramic restorations have gained more popularity due to their high esthetic, high improvement in their fracture strength, and good biocompatibility properties [39]. These restorations are luted in position with a resin cement to tooth structure after using bonding agent [40]. Micromechanical retention of the luting cement to the restoration is obtained by etching the fitting surface of the crown with hydrofluoric acid. In addition, the ceramic surface is treated by a silane bond enhancing agent. These agents have been suggested to use for improving the bond strength to resin-based cements [41]. This luting procedure is used to provide bonding at both the dentin-luting cement and luting cement-ceramic crown interfaces [42].

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4. Test methods in adhesive dentistry

Laboratory tests are useful for testing new operative techniques and materials before they are clinically implemented. The methods employed, however, should meet the following requirements (FDA 1978): The results must be reproducible, the parameters which influence the test results must be known, the variability of the measured values must be low and within an acceptable range and if devices are employed for the test itself and/or to measure parameters and posttesting conditions of the specimens, then these devices must be suitable for the given purpose, that is, they must be qualified. These requirements were described for medical devices and compiled under the name "Good Laboratory Practice" [43].

Flexural strength, composite resin	699
Flexural strength, fiber post	50
Flexural strength, ceramic	491
Elastic modulus, composite resin	570
Elastic modulus, fiber post	96
Elastic modulus, ceramic	518
Shear bond strength, composite resin	2240
Shear bond strength, fiber post	30
Shear bond strength, ceramic	853
Tensile bond strength, composite resin	2222
Tensile bond strength, fiber post	95
Tensile bond strength, ceramic	497
Dynamic fatigue, composite resin	24
Dynamic fatigue, fiber post	5
Dynamic fatigue, ceramic	51
Push-out, composite resin	191
Push-out, fiber post	217
Push-out, ceramic	58
Pull-out, composite resin	52
Pull-out, fiber post	40
Pull-out, ceramic	54
Fracture toughness, composite resin	261
Fracture toughness, fiber post	9
Fracture toughness, ceramic	422
FEA, composite resin	345
FEA, fiber post	96
FEA, ceramic	562

Table 1. Searching PubMed with chosen keywords (March, 2016).

Nowadays, numerous new adhesive systems are put on dental markets. *In vitro* test methods are necessary to evaluate test materials' suitability for the clinical and physical properties within reasonable conditions. **Table 1** shows the PubMed analysis of adhesive materials and test methods used in dentistry with chosen key words.

Adhesion quality of adhesive materials on enamel and dentin may be quantified using several methodologically distinct approaches [44], roughly divided into macro- and microsetups, depending on the size of adhesion area. The macrobond strength can be evaluated with shear or tensile mode, a push- or pull-out methods at a bonded area larger than 3 mm^2 [45]. The ability of microbond strength tests is to evaluate the effect of local tooth structure on bond strength [46, 47] and to allow depth profiling of different substrates [45].

4.1. Flexural strength and elastic modulus

The flexural or bending strength is a measure of the fracture resistance of a material. For restorative materials in occlusion bearing areas, the ISO standard demands a flexural strength of at least 80 MPa [48]. For this test, bar-shaped specimens (25 × 2 × 2 mm) are made, stored in water for 24 h and at 37°C, and loaded until failure in a universal testing machine (crosshead speed 0.75 mm/min [±0.25]). The flexural strength in three-point bending test is calculated with the following formula:

$$\mathrm{BF} = 3Fd / 2wh^2$$

where F is the maximum force, d is the distance between the two anchors, w is the width of the specimen, and h is the height of the specimen.

Because the flexural strength changes after water storage, the value at 24 h only provides limited information. Reliable data on the behavior of the material are obtained when the value after 1-day storage is compared to that after 1 month of water storage [49].

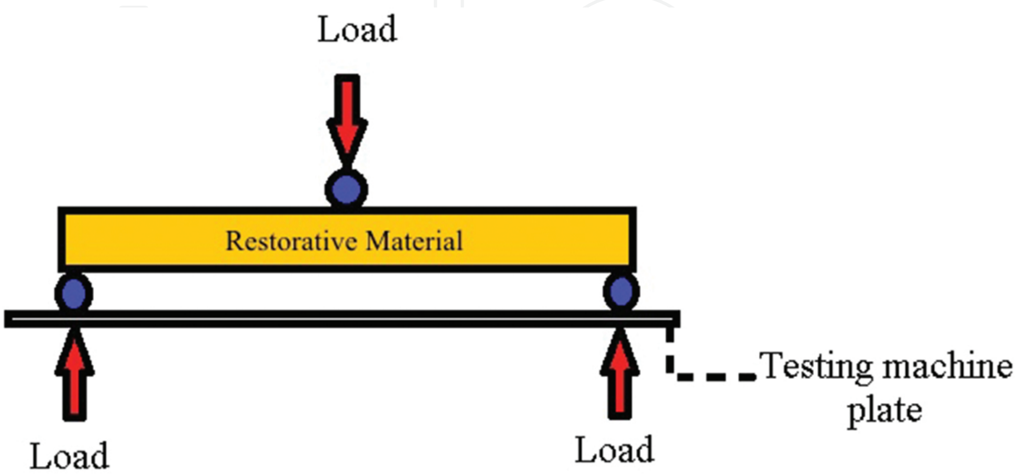

Figure 3. Schematic presentation of a three-point bending test.

The elastic modulus of the dental restorative materials should be close to that of the enamel and dentin to allow better stress distribution. The existence of large modulus gradient between restorative materials and dental hard tissues may lead to fracture [50]. Elastic modulus represents the stiffness of a material within the elastic range when tensile or compressive forces are applied [51]. A bar-shaped sample fixed at three points is loaded to failure in a testing machine at a crosshead speed of 0.5 mm/min (**Figure 3**). The elastic modulus can be read from the stress-strain diagram [49].

4.2. Shear bond strength measurement

In macroshear strength tests, composite cylinders with a diameter of about 3 or 4 mm are adhered to flat ground tooth tissue (dentin or enamel) surfaces after application of the adhesive systems and then sheared off with a special testing machine (**Figure 4**).

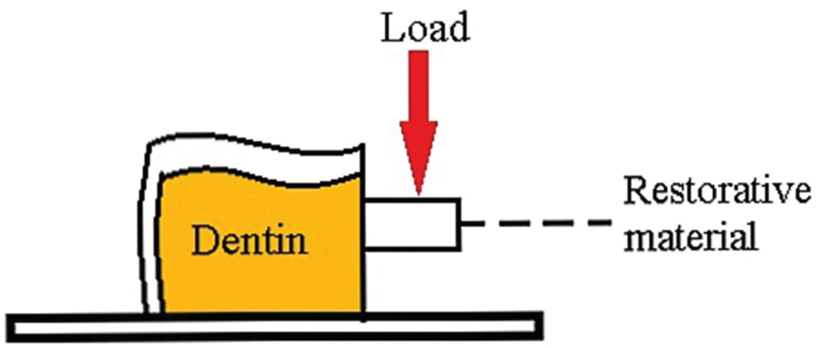

Figure 4. Schematic presentation of a shear bond strength test.

The force in Newtons required to debond the composite cylinder from the substrate is measured. Finally, this force is applied parallel to the area of the bonding surface to yield the bond strength in megapascals (MPa = 1 N/mm^2) [49]. The stress distribution is seen as a disadvantage in shear strength testing. For instance, enormous forces are exerted on the site at which the shearing blade contacts the specimen [52]. The absolute bond strength also depends on whether the shearing blade is flat or if it bears a notch which surrounds half of the specimen [53]. After preparing samples, test is applied immediately, after 24 h or after up to several months of water storage at 37°C [45].

Special jigs have been prepared which have different configurations such as wire loops, notched chisels, and knife edges are used to apply shear force. A knife-edge chisel causes severe stress concentration at the force application area; however, wire loop and the notched chisel render a more even stress distribution at the edge of the bonding area [52]. Peak stress during application of force by blunt knife edges may explain the frequently observed cohesive composite failure close to loading point [54].

Microshear bond strength test is applied on bonded cross-sectional areas of 1 mm^2 or less [55]. This test permits efficient screening of adhesive systems, regional and depth profiling of a variety of substrates and conservation of teeth. Aqueous storage durability studies are also possible microshear bond strength due to the relatively short diffusional distances (0.02–0.05 mm) from the cavosurface [56]. In the microshear bond strength, specimen is prestressed prior to testing only mold removal. The use of the mold for restorative materials placement can lead to introduction of flaws and different stress concentrations upon shear loading [57]. Microshear bond strength tests are influenced by a number of factors including the thickness of adhesive layer, size of bond area, cross-head speed, the mechanical properties of adherent and adhesive and debonding procedure [55, 58]. The failure of this test method is attributed to crack initiation by tensile forces as well as shear forces that imply that a fracture mechanics approach may also be important [59].

4.3. Tensile bond strength measurement

In a tensile test, composite cylinders are adhered flat dentin or enamel surfaces and tensile force may be exerted on composite cylinders using chucks or conical composite plugs employed instead of cylinders [60]. The macrotensile bond strength test was used as frequently as the macroshear bond strength test, in 1991 to 2001 [61]. The specimen can be held by active or passive gripping technique. Active gripping technique involves mechanical locking of specimen to gripping device, such as glue or clamps, whereas in passive gripping technique, specimen is placed in a testing machine without the aid of glue or clamps or mechanical gripping [62]. Currently, the macrotensile bond strength test is not common, but it is still important to measure bond strength to restorative materials such as ceramics and metal alloys [63, 64].

It was observed that tensile bond strength is inversely related to bonded surface areas and that although much higher bond strengths were measured, most failures still occurred at the interface between tooth substrate and adhesive [55, 65].

For specimen preparation, the adhesive is applied to prepared dentin and a large restorative material plug incrementally polymerized onto adhesive. After storage duration, this assembly is sectioned using precision circular saws into 1-mm thick slices, which are then cut into sticks of about 1 × 1 mm [45]. Some approaches trim such sticks to dumbbell or hourglass shapes [66, 67]. After specimen preparation, specimens are mounted on a variety of jig designs using fast setting glues to standardize sample fixation to the universal testing machine for loading [68, 69] (**Figure 5**).

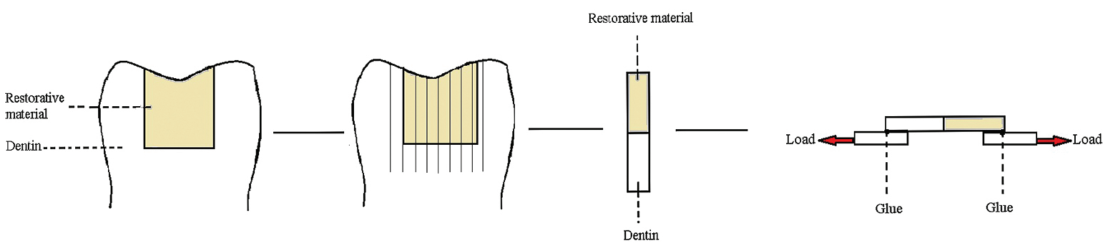

Figure 5. Schematic presentation of a microtensile bond strength test.

The advantages of this method are that, only a few extracted teeth are required, regional dentin differences can be examined and it is easier to distinguish between different materials, the better stress distribution at the true interface, ability to test irregular surfaces and very small areas and facilitates microscopic examinations of the failed bonds due to smaller areas [70, 71]. The major disadvantage of microtensile bond strength test is the rather labor-intensive, technically demanding and relatively fragile sample preparation technique. Sawing and trimming of the test samples appear to be the most technique sensitive part of microtensile bond strength test [70]. Interfacial stress during sample preparation is reflected by the number of pretest failures, as often occurs with lower-performance adhesives or on brittle substrates [45]. Special care should be taken to avoid/reduce the production of microfractures at the interface during specimen preparation. They may weaken the bond and, thus, reduce the actual bond strength [72].

4.4. Dynamic fatigue measurement

Fatigue can be defined as the failure of mechanical properties after repeated applications of stresses, at a level well below the ultimate fracture strength of the material interface [73]. During the restoration survived in mouth, a restoration is sustained to cyclic loading, in the long term this loading may possibly lead to marginal deterioration and loss of the restoration [12]. Therefore, fatigue testing of dental adhesives is expected to better determine their performance. But also, there is no standard fatigue test for dental adhesives. Possible methods are a cyclic shear test [74], a cyclic tensile test [75], or a cyclic push-out test [76]. Another possibility is loading not only the interface but the whole tooth until the tooth-restoration complex fails [77]. A microrotary fatigue device has been developed for dynamic tests of tooth-composite interfaces [78]. In this method, bar-type samples prepared with a rounded, constricted interface were clamped in a pin-chuck and connected to a stepping motor with the free end loaded with a certain weight. By rotating the specimen, each spot at the outer surface of the interface undergo compressive and tensile loading [79].

4.5. Push-out and pull-out test methods

Push-out method was first described by Roydhouse in 1970 [80]. Conical preparations are made in teeth and filled with restorative material. Beginning at the pulpal axial wall, dentin is removed up to the level of restoration, which is pushed out with the testing machine's plunger. Specimen preparation is also simplified by cutting dentin into disks and making conical preparation in it. Then the disk is placed on a glass plate and the restorative material is inserted into the cavity [49] (**Figure 6**).

The advantages of this method are the simultaneous testing of marginal seal and adhesive bond on the same specimen [81], and taking into account the effect of polymerization stress might have in the clinical situation [74]. The disadvantage of this method is that minor degrees of composite swelling upon water storage can induce a significant amount of friction, independent from the adhesive performance [45].

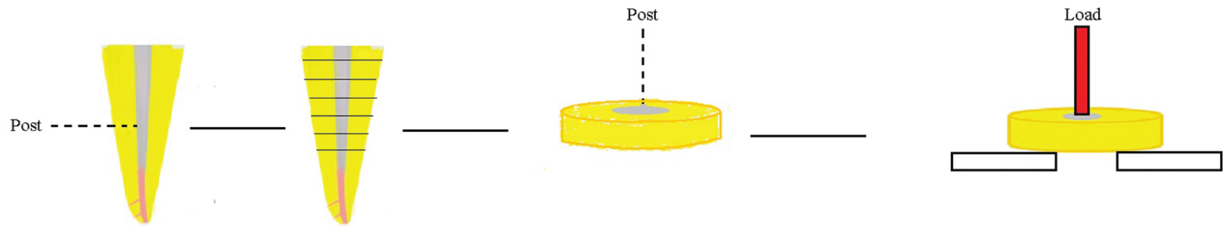

Figure 6. Schematic presentation of a push-out test.

In this method, the plunger must provide near complete coverage of the testing material without touching the root canal walls. This method is very commonly used in the analyses of post and root canal sealers adhesion in root canals. The bond strengths of cements for ceramic restorations are also measured with this method [49].

Micro push-out test is a modification of push-out test where the specimen thickness is less than or equal to 1 mm^2. Micro push-out is more dependable than microtensile bond strength test while evaluating the bond strength of luted fiber posts [82]. Castellan et al. showed that a modified push-out and microtensile bond strength test revealed higher values than traditional conventional push-out and pull-out tests [83].

A novel approach to the pull-out test was designed to eliminate the region of weakness in the postcement system, which was elsewhere reported to be sometimes the predominant failure modes. The pull-out method allows comprising the whole length of the root canal because the focus was not on regional differences in bond strength. The postcemented roots were not

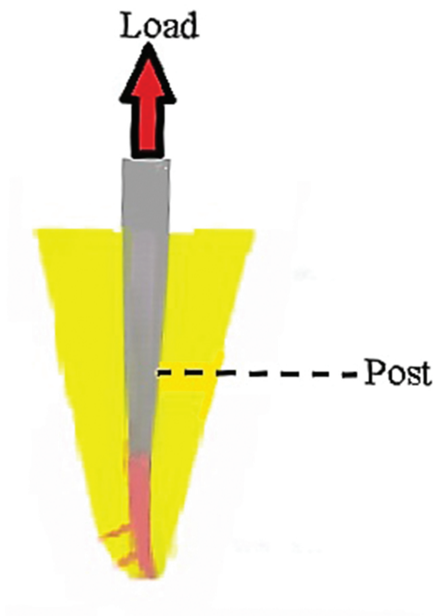

Figure 7. Schematic presentation of a pull-out test.

sectioned, so potential artifacts or premature failures caused by preparation of the specimens could be avoided [84] (**Figure 7**).

4.6. Fracture toughness

Interfacial material properties, such as crack growth resistance, are described by linear elastic fracture mechanics. Fracture mechanics is well established in the engineering community to describe the properties of monolithic materials and is becoming increasingly common to investigate the interface of dissimilar materials [85, 86]. Fracture toughness can be defined as a measure of the material's resistance to crack propagation [73]. Fracture toughness relates a loaded sample's ability to resist flaw propagation to its mechanical durability. Flaws appear as cracks, voids, metallic inclusions, weld defects, design discontinuities, or a superimposition of the above, and are considered an unavoidable consequence of specimen processing, fabrication, or service of a material/component. Fracture toughness of materials is described by the stress intensity factor (*K*) that combines load, crack size, and structural geometry. A Roman numeral subscript is used to indicate fracture mode. Mode I fracture is the most common mode and attributed to a crack plane orthogonal to the highest tensile load. The stress intensity factor is represented by the following equation:

$$K_I = \sigma\sqrt{\pi\alpha\beta}$$

where σ is the applied stress (MPa), α is the crack length (m), and β is the individual geometry factor.

According to the differences in mechanical properties, the stress distribution between the joint components follows complex patterns. *In vitro* analysis of dental adhesives is further complicated by residual polymerization stress, in homogeneity of the tooth substrate and interface (adhesive layer, hybrid layer, prism, tubule orientation, etc). Even tensile stress distribution occurs only if none of the involved components deforms laterally under tension, or if the same deformation results from tensile stress applied orthogonally to the adhesive [45].

The concept is to initiate and propagate in a stable manner a crack through the bonded interface using either the chevron notch short rod or bar design [87–89] or a modification of the chevron notched short rod known as the notchless triangular prism [90, 91] or the single-edge notched beam [89].

Differently sized specimens, even when of identical proportions, give different values for K_I stress intensity factor, since stress acting adjacent to a flaw of a given size is influenced by specimen dimensions up to a critical dimension. Beyond this critical dimension, the value K_I becomes a true material property called the plane strain fracture toughness (K_{IC}). The stress intensity K_I represents the level of stress at the tip of the crack, and the fracture toughness K_{IC} denominates the highest stress intensity a material under plane strain conditions can withstand without fracture. Fracture toughness or the strain energy release rates are tests that are considered more meaningful to measure the energy or work to separate the adhesive resin from its bond to dentin [92].

Specimen preparation for fracture toughness test is difficult and no standard procedure for dental adhesives is available [73]. Also, it is not possible to prepare multiple specimens from the same tooth. One point of concern is presence of resin flashes extending out of the chevron, if the required notch is prepared with Teflon tape. These flashes may increase the values measured [89, 93] also can be avoided if groove cuts are prepared afterward [94]. On the other hand, the prepared grooves are more apt to microcracks, which may act as crack initiators and so lower the interfacial fracture toughness [73].

In all studies on fracture toughness, failure analyses revealed primarily interfacial failures, in accordance with observed clinical failure modes [95].

4.7. Finite-element analysis

The finite-element analysis (FEA) is an upcoming and significant research tool for biomechanical analysis in biological research. It is an ultimate method for modeling complex structures and analyzing their mechanical properties. FEA has now become widely accepted as a noninvasive and excellent tool for studying the biomechanics and the influence of mechanical forces on the biological systems. It enables the visualization of superimposed structures, and the stipulation of the material properties of anatomic craniofacial structures [96]. It also allows to establish the location, magnitude, and direction of an applied force, as it may also assign stress points that can be theoretically measured. Overall stress distribution within the tooth/restoration complex is determined by not only geometry and material arrangement, but also material properties, fixation, and loading conditions determine stress distributions [97].

FEA is an analyzing method for stresses and deformations in the structures of any given geometry. In the FEA method, the computational model is developed based on the modular principle and is made from many finite size elements, thus, it is well adapted to the real structures. This procedure is called discretization [98]. The steps followed are generally constructing a finite-element model, followed by specifying appropriate material properties, loading and boundary conditions so that the desired settings can be accurately simulated. Various engineering software packages are available to model and simulate the structure of interest [99].

Most models consider isotropic behavior, since it is not possible to quantify the whole anisotropic structure of a bone, organ with current techniques [100]. The load is applied either to the tooth or to the bone as required. Although, the muscle activity and craniofacial morphology affect the occlusal load in actual clinical situation, it is presently difficult to simulate individual muscle forces to FEA modeling. So, usually vertical or oblique load on the teeth or materials is used as an input load in FEA [101, 102].

FEA has been useful to predict stress distributions within teeth and at the interface of adhesives and dentin. This modeling requires knowledge of the strength of materials vs. the strength of mineralized dental tissues and the differences in elastic moduli of materials versus dental tissues. Then 3D stress distribution within these structure can be calculated during varies types of loading [70].

http://dx.doi.org/10.5772/63773

The results of an FEA are expressed as stresses distributed in the structures under investigation. Using FEA during adhesive testing, applied stresses may be shear, microshear, tensile, microtensile, compressive, etc., or a combination known as von Misses stresses. von Misses stresses depend on entire stress field and are a widely used indicator of the possibility of damage occurrence [103] (**Figure 8**).

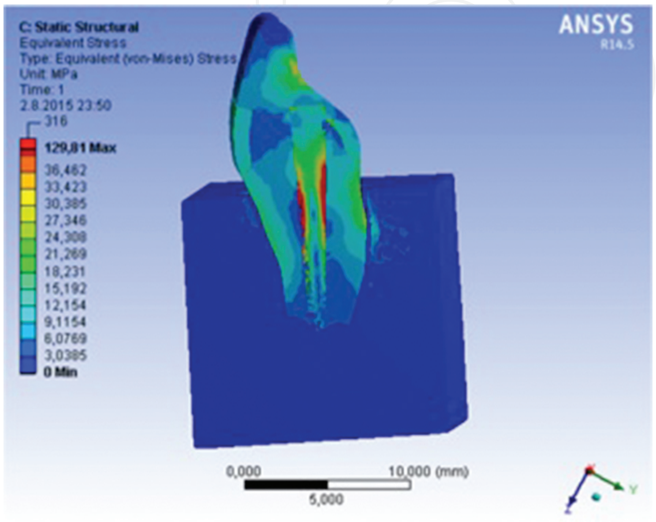

Figure 8. Distribution of von Misses stresses (MPa) in the post and core systems. Blue to red colors represent stress values from lower to higher, respectively. (Dr. N. Güven, Dr. Ö. Topuz).

5. Conclusion

During the past decades, restorative concepts have been continually changing and adhesive technology has become more important. In adhesive dentistry, many kinds of adhesive materials have been using in order to restore damaged tooth structures. Although the materials used in adhesive dentistry approach the properties of enamel and dentin, it is not always possible to replicate their mechanical behaviors. For evaluating adhesive materials' suitability for the clinical and physical properties within reasonable conditions, *in vitro* test methods are necessary. The similarity of elastic modulus and flexural strength between restorative materials and tooth structures is important. The elastic modulus of materials can be tested by a three-point bending test. The macrobond strength can be evaluated with shear or tensile mode, a push- or pull-out methods at a bonded area larger than 3 mm^2. The ability of microbond strength tests is to evaluate the effect of local tooth structure on bond strength and to allow depth profiling of different substrates. Finite-element analysis is useful to predict stress distributions within teeth and interface of adhesives and dentin. This modeling requires knowledge of the strength of materials vs. the strength of mineralized dental tissues and the differences in elastic moduli of materials versus dental tissues. These test methods used in adhesive dentistry are useful for testing new operative techniques and materials before they are clinically implemented.

Author details

Mügem Aslı Gürel[1], Bağdagül Helvacıoğlu Kıvanç[1*] and Hacer Deniz Arısu[2]

*Address all correspondence to: bagdagulkivanc@gmail.com; bagdagul@gazi.edu.tr

1 Department of Endodontics, Faculty of Dentistry, Gazi University, Ankara, Turkey

2 Department of Operative Dentistry, Faculty of Dentistry, Gazi University, Ankara, Turkey

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