Fiber-reinforced adhesive bridges

Clinical and laboratory performance

Celeste van Heumen

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by

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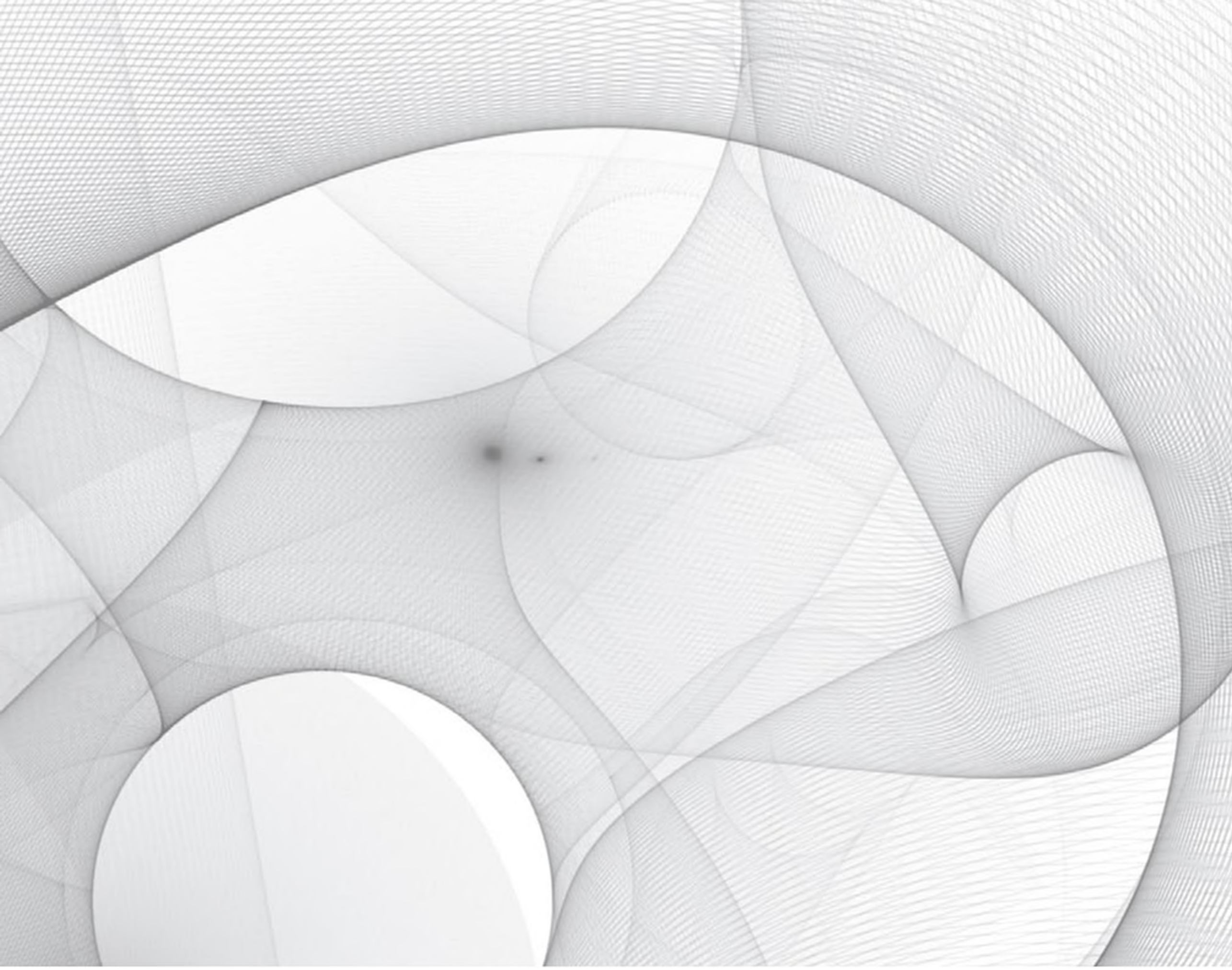

Chapter 1

General introduction

Abstract

This chapter provides a brief literature overview of tooth-replacing fiber-reinforced fixed partial dentures. Material properties and material design factors of fiber-reinforced material are described. After consideration of limitations in performance of these kind of restorations, in particular for the anterior area, the objectives and outline of this thesis are described.

Introduction

Background

Restorative dentistry is genuinely changed with the large scale use of adhesive techniques in dentistry. It is now possible to make restorations with a tissue saving character, in particular because of adhesion between material and tooth. In the reconstruction of carious or fractured teeth, only the weak affected tooth tissue should be removed after which the tooth can be restored by applying the restorative material. This is in contrast to the conventional techniques for which a retentive cavity should be prepared into the tooth crown. This is often accompanied by the removal of sound tooth material, in order to obtain specific retentive and resistant features. Besides, the adhesive materials are generally tooth colored resin materials, while the number one conventional restorative material was a dark grey metal amalgam. Patients prefer tooth-colored restorations and by coincidence they are of a minimal invasive character. Adhesive materials are now also used in large single unit restorations instead of cast metal or metal-ceramic restorations. It is anticipated that the adhesive materials may require more maintenance in these kind of constructions. These procedures are accepted, stipulated that a good informed consent is given [1, 2].

With the change to adhesive, minimal invasive single unit restorations, also the multi-unit bridge-like restorations to replace absent teeth have changed. Different treatment options for these so-called fixed partial dentures (FPDs), including conventional bridging and metal resin-bonded FPDs, have different indications that have changed during time. The tissue saving character influences the choice of certain treatment options. The conventional approach is based on a pontic attached to adjacent crowns. Therefore, preparation of abutment teeth to create mechanical retention is needed. Adhesive bridging is generally known for its tissue saving character. Adhesive resin-bonded FPDs consist of a framework of metal or composite, with the pontic attached to the framework. Adjacent teeth, or abutment teeth, are usually provided with only slight preparation to create occlusal space and mechanical retention for the framework.

In the past different types of metal resin-bonded FPDs have been applied. The first designs of adhesive FPDs developed by Rochette consisted of perforated wings and have been presented as a temporary solution [3, 4]. The connection between restoration and tooth is achieved by adhesive resin cement, but the bonding to the metal framework mainly relies on the mechanical retention of the perforated wings.

A further development, the so-called Maryland bridge consists of non-perforated wings and the retention is mainly based on the adhesive strength of the luting cement to the metal and the enamel. This type of resin-bonded FPD is still widely used and offers a viable (semi) permanent replacement of absent teeth, if indicated correctly. Contra-indications, for example, are a relatively long span and the replacement of teeth which have to withstand very high loading forces, such as the canine or posterior teeth. It is considered to be a conservative and practical approach in dentistry. The metal resin-bonded bridge has its roots in the nineteen eighties and has been researched quite extensively in the past decades [4-6].

Clinical performance of adhesive tooth-replacing restorations

A meta-analysis of 60 publications on resin-bonded FPDs reported a survival rate of 74% after 4 years [7]. Two recent studies indicate a better survival. Clinical survival data on metal alloy resin-bonded FPDs have been reported to be 60% and higher after 10 years [8, 9].

Despite the adhesive connection between restoration and teeth, debonding of the resin-bonded construction is a well-known failure mode. Debonding often is a result of insufficient adhesive strength between resin cement and metal and insufficient mechanical retention [10-12]. Besides, during time the retentive capacity of the resin cement is decreasing [13]. The resulting debonding can be explained by metal fatigue after constant stress and hydrolysis of the adhesive interface. Research has shown that the retentive strength of metal resin-bonded FPDs may be increased by modification of the mechanical retention by tooth preparation [14].

Nowadays, the demand for tooth-colored restorations has been increased and metal resin-bonded FPDs do not meet to this demand completely. Another disadvantage is the sometimes grey shadowing of the metal frame through the abutment teeth. Therefore, resin composite can be an interesting material for the construction of adhesive FPDs, considering adhesive features and the color. However, the tensile strength of resin composite seems to be insufficient to use this material for bridging applications. Adding a reinforcing material such as fibers to improve the resin composite properties can be the solution.

Fiber-reinforced materials

Fiber-reinforced resins as known today, have been developed since the mid-twentieth century in various applications. Originally these materials were applied in military airplanes, but soon it appeared that these materials could be applied in many common objects. For example tennis rackets, fishing rods and flagpoles can (partly) be made from fiber-reinforced materials. For these kind of applications a base material such as polymer synthetic materials are used, in which fibers are intercalated. The combination of synthetic material and fibers results in a hybrid construction with high strength and a relatively low weight. These properties can be advantageous in heavy loaded constructions that were performed in metal before, such as shiphulles or airplanes.

Despite the large scale application in industrial products, the experience with replacement of metals by fiber-reinforced materials in dentistry is still limited. Industrial materials are not always appropriate for oral application. One of the reasons is toxicity. Besides, fiber-reinforced materials in industrial applications are mostly applied in constructions of relatively big size, in contrast to dental constructions which are mostly small. However, certain types of fibers can be combined with dental composites. In this way, fiber-reinforced adhesive materials can be made, which can be applied in various dental applications such as bridging composite constructions.

During the past 20 years, on a limited scale, a variety of fibers has been used for different applications in dentistry. Fiber reinforcement already were used for applications in which polymers have demonstrated their value, such as full dentures and temporary solutions [15].

Use of fiber-reinforced materials in tooth replacing restorations

An advantage of fiber-reinforced composite (FRC) compared to metal resin-bonded FPDs is the tooth-colored property. An additional advantage is the less extensive work by the dental technician compared to the foundering procedures in metal ceramic restorations. The non-cured composite material is normally applied from the package directly to the construction to be made en light cured. The construction can be made on plaster casts in the laboratory, or directly in the patients' mouth (indirect vs. direct technique).

The direct technique consists of the application of resin composite and fiber bundles directly in the patients mouth to create a tooth replacing restoration. This technique characterizes itself by the one-phase readability and ease of working. The retentive strength of the construction depends on the direct bonding of composite to enamel or dentin, without an extra luting agent interface. Indirectly applied by the dental technician the resin composite mostly is a so-called laboratory composite, that requires oven curing to optimize polymerization. Design and styling on a cast model are relatively simple compared to the direct technique. By post-curing in the oven it is generally expected that material properties will improve, such as tensile and loading strength. However, reports on the effects of post-curing show different results [16, 17]. Well polymerized, cross-linked polymer matrix with a high conversion rate of the resin molecules is more difficult to adhere to than non-annealed resin composites. Therefore additional measures are required, such as sandblasting, adding silane coupling agents and the use of intermediate monomer resin (IMR) [18, 19].

An extra possibility of the use of FRC material is the fact that the direct and indirect techniques can be combined, which is a consequence of the adhesion between cured composite and newly applied composite. The indirectly made construction can still be adjusted after placement with directly applied composite. With the conservative metal-porcelain constructions this is hardly possible.

Fiber-reinforced composites have a higher elasticity modulus compared to metals, resulting in lower stress in the adhesive layer. This makes FRC constructions promising. However, the clinical performance shows restrictions. Delamination of the overlying veneering composite of the frame construction has been described several times [20]. Meanwhile failures resulting from debonding from the tooth or actual fracturing of the fiber framework have been reported less [21, 22]. In various studies differentiation has been made between initial cracks and final fracture of the construction and these type of failure do seem to coincide with differences in applied load [23]. In conclusion, adhesion of the (veneering) composite to the fiber framework apparently needs improvement to support general use of the fiber-reinforced restoration in dentistry [24].

Material composition and properties

Composite materials are made of at least two different chemical components. For purpose of reinforcement of the composite material, the individual positive material properties of the different components are combined. In composites one component functions as connecting material, so-called matrix, and the other component serves to strengthen the matrix. This reinforcing component is called the filler, which can be particles or fibers.

In dentistry a composite is commonly a mixture of an acryl monomer matrix with particles polymerized in it. Size and number of particles, composition of the matrix, adhesion between particles and matrix, and the polymerization condition are influencing the composite properties. Filling particles usually exist of silica-glass particles. To improve the adhesion between particles and matrix, silane coupling agents are used. By mixing different particle sizes, properties as toughness, stiffness and wear resistance can be influenced.

Composite is an isotropic material without specific orientation of filling particles. This means that mechanical and thermical properties of composite do not vary from different directions. A disadvantage of composite is the limited shear force strength and tensile strength. This limitation especially expresses itself when composite is applied in bridging constructions, in particular the posterior area. In bridgework a span is created, in which support of underlying tooth material is missing. As a consequence of occlusal forces, tensile stress will occur in the material.

By adding filler materials with a certain orientation, such as glass fibers, aramid fibers, carbon fibers, or UHMWPE (ultra high molecular weight polyethylene) fibers to composite materials, the material becomes anisotropic. As a consequence composite materials can be modified to be used in bridging constructions. By adding fibers high strength and stiffness is achieved in one direction of loading, and for plastics these are substantially higher with fibers, than without [25]. It is interesting to note that fibers are not elastic and are thin with a diameter of 7 to 20 μm.

Mechanical properties are influenced to a great extent by the direction in which fibers are orientated and generally distinction of reinforcement is on the basis of the different fiber orientations. Incorporation of unidirectional fiber bundles, that exist from 1000 to 200.000 single fibers in dental applications, results in anisotropy. The behavior of the construction is different at loading from different directions. Bidirectional fiber materials consists of woven fibers, with a fiber orientation in 2 or 3 directions, resulting in orthotropy. Finally, there are random oriented fiber structures, which can be distinguished in long and short random orientated fibers. Incorporation into a resin composite material results in isotropy [26]. This is comparable to composite, in which the filler particles are replaced by small fibers.

Tensile strength is highest when the material is loaded in a direction that leads to loading of the fibers by pulling. It is important that tensile forces of the construction are conduct into longitudinal direction of the fibers. In this way fibers are pulled as strings in the construction by loading. Bundling of fibers increases the diameter and thus strength increases. Impregnation of the fiber bundle with a synthetic (matrix) connects fibers bilateral, resulting in a higher tensile strength compared to a fiber bundle without matrix. The matrix absorbs mechanical stress, creates stiffness and passes over the loading from one fiber to another. That is why bonding of fibers and polymer matrix is important.

Stresses that originate in a dental bridging construction during loading can broadly be divided into compression stress on the occlusal side, tensile stress on the cervical part and shear stress next to the abutment teeth. Bending of the construction at the mid-cervical part because of loading on the occlusal side will increase the tensile stress at the cervical part. Theoretically, at the mid-cervical area of the construction the most problems like fracture will occur. Reinforcement of this area should consist of application of fibers, considering a perpendicular relation of fibers and tensile stress.

In literature the influence of fiber location in composite is described. Most studies describe the use of some long fiber bundles, placed in (a part of) the restoration [27, 28]. Location of fiber bundles in the construction was varied and showed an influence on tensile strength. The fiber location has an effect on the bending strength of the material. In studies that describe three-point bending tests of fiber-reinforced composite beams with fibers incorporated at various locations, it is shown that the load resistance is highest when the fiber bundle is located at the tensile side of the construction [27-31]. If fiber bundles are placed in vertical direction, from compressive side to tensile side, the stiffness of the construction increases [29]. Considering the fact that strength of the material and construction is depending on the direction in which fibers are placed in the construction, the location of the fiber bundle is very important.

Concluding, it can be stated that mechanical properties can be influenced by the design of the composite material, for example the orientation of fibers, type of fiber and fiber structure (geometry) [32]. This is called crossectional arrangement or design.

Fibers and their properties

The strength of unidirectional reinforced composite material is linked to the main orientation of the fibers, longitudinal or transversal. The most used fibers (glass, carbon and polyethylene) approximately have a linear elastic behavior until fracture. They have a much higher stiffness and strength than the composite matrix. Below some characteristics of the most often applied fiber materials are described.

Glass fibers

The main part of glass fibers is Si-oxide (mostly quartz). Other oxides can be added, such as B, Al, Ca, Na, K, and Mg, which influences the properties of glass. Multiple glass fiber types have been developed in this way. Most applied is the E-glass fiber (alumino-borosilicateglass), originally meant for electro technical goals because of its electron conducting ability. Advantages of glass fibers are the strength, transparency, and relatively low costs. However, their stiffness is moderate and glass fibers easily show cracks at the surface. Glass fiber composites are thus mainly applied when not stiffness is qualifying, but strength.

Carbon fibers

Carbon fibers have been developed in the early sixties. In fact these are synthetic fibers that were charred by heating them to a temperature over 2000 °C, to leave the carbon atoms only, arranged in a hexagonal graphite structure. When these graphite plates are arranged parallel in length, a fiber with high strength and stiffness is created. However, strength is considerably lower in transverse direction than longitudinal. Carbon fibers are chemically inert and invulnerable for moist. A disadvantage for dental applications is their black color.

Synthetic fibers

After the development of carbon fibers, ultra-strong synthetic fibers were developed, such as aramid fibers (Kevlar or Twaron) and polyethylene fibers. Aramid fibers belong to the organic, synthetic fibers. They can be distinguished by polyamide (nylon) because of C-atoms that are included, and therefore they are substantially stronger and stiffer. Moist has a negative influence to the strength. Adhesion to the composite matrix is nearly impossible with aramid fibers and is more difficult with polyethylene fibers than with glass or carbon fiber types.

Fiber related properties

In Table 1 some examples of fibers that are used in dental applications are shown. Brands of fibers are distinguished according to the type of fiber and the fiber orientation and pre-impregnation are described. Some properties of fiber-reinforced composite materials are depended of the characteristics as described in the table and the main properties are:

- Stiffness and strength of the material: fibers that are positioned parallel to each other, will maximize the increase of stiffness. Stiffness of carbon fiber reinforced composite can be increased up to 50 times compared to unreinforced composite.

Dyer et al [33] showed that strength is increased most with unidirectional oriented glass fibers. Alteration of fiber direction (i.e. randomly oriented FRCs) changes maximum possible load of the material [27].

- Thermo mechanical properties of the FRC: thermal expansion in longitudinal direction is higher compared to transversal direction, because fibers expand in longitudinal direction only, which can result in internal stress. These forces are relevant from a clinical point of view in the long term stability of restorations. For example, veneering composite can delaminate because of varying thermic coefficients of materials resulting in stress of the interface [34].
- Polymerization shrinkage: in transversal direction shrinkage of the matrix is possible, which can be explained by the anisotropic character [35]. It is not clear whether fibers and matrix separate by this shrinkage.
- Adhesion of fibers to the matrix: research has shown an improvement of mechanical properties when adhesive strength between fibers and matrix increases [36]. To achieve a sufficient adhesion between fibers and matrix, fibers are impregnated with a high viscous resin. An effective impregnation process allows the resin to come into contact with the surface of every fiber which can be performed manually or industrially. For glass fibers, one method is industrial preimpregnation of the reinforcing fibers with highly porous linear polymer, after which further impregnation with BisGMA-TEGDMA based light polymerizing monomer resin is performed when the reinforcement is used. In this way a PMMA-dimethacrlyate semi-inter polymer network (IPN) is formed between the reinforcing fibers, which results in a well impregnated end-product [37-39]. The fiber-matrix adhesive strength of glass fibers compared to carbon fibers is significantly higher [26].
- Adhesion of fiber reinforced material to veneering resin composite: fiber bundles are surrounded by the resin. When the fibers of the FRC are exposed threw the resin matrix, the adhesional properties of the fibers it selves play a role in adhering the veneering composite to the FRC. In this respect, the most suitable fibers are glass and silica fibers which can be silanated to obtain an adequate adhesion to the polymer matrix [38]. Besides, different fiber orientations show variation in adhesive strength to resin material.
- Fiber volume: the higher fiber volume in a bundle, the higher tensile strength (in fiber direction) of a construction is [25]. The girth of the fiber bundle increases, resulting in a higher strength. It is known that fiber fractions of 65 wt% for fully resin impregnated glass FRCs can be obtained and strength of the construction is related to the relative fiber quantity in the cross-section of the material [38, 40]. Consequently, the FRC material is stronger when the fiber volume is higher [41, 42].

- Water resorption of the matrix: the composite matrix allows diffusion and absorption of water, as a result of the polarity of polymers. This results in a decrease of strength and stiffness. When water diffuses through the polymer matrix and reaches the interface between the silanized surface of the fiber and the polymer, hydrolysis may occur, which decreases the physical properties of the glass FRC. It is reported that the greatest reduction in strength takes place in the first 4 weeks, when the material is water stored. When glass fiber volume increases, the effect of water resorption is less [43]. Further, it appeared that there is not a great difference between unreinforced and reinforced composites, for strength, which implies that this mainly is caused by water resorption in the matrix and not by the effect on the interaction between fibers and matrix [43]. Its effect on the clinical use is not quite clear. However it is clear that FRCs strength decreases by mechanical and chemical influences.

Table 1 Characteristics of different fiber types

Fiber type	Brand	Fiber orientation	Pre-impregnation
Polyethylene	Ribbond	Woven	No
	DVA fibers	Unidirectional	No
	Connect	Bidirectional	No
Aramid	Fiber Flex (Kevlar)	Unidirectional	No
	Twaron	Unidirectional	No
Glass	GlasSpan	Bidirectional	No
	Fiber-Splint	Woven	No
	Vectris	Woven/Unidirectional	Monomer
	Fibre-Kor	Unidirectional	Monomer
	Stick/Everstick	Unidirectional/Woven	Polymer

Fiber application in the construction

The design of tooth replacing restorations is based on a pontic that is attached between the adjacent abutment teeth. The part of the construction that connects the pontic to the abutment tooth is called connector. A bridge characterizes itself as an overlying construction, in which the abutment teeth function as support against occlusal and shear forces. This occlusal support deviates from mechanical retention forms, such as a full crown or a conventional FPD, to adhesive retention forms, such as the interface between luting resin cement and tooth material of a resin-bonded FPD. The weakest part of the construction in conventional bridgework is the connector area. This part of the construction withstands the highest tensile and shear forces while it has the lowest material volume [44, 45]. Also in FRC FPDs it is most probably the connector to be the weakest part of the restoration [46]. Cracks or fractures may develop from this region [47]. The pontic is a volumous composite entity that is not at risk to fracture, but the connector in the FPD is relatively thin and is more fragile [48]. It is assumed that a higher volume of composite in the pontic decreases the risk of fracture to a great extent.

One of the phenomenons that are described, is the fact that fractured parts of the fiber-reinforced material have been connected by the fiber bundles after failure. Another FRC material property is the function of the fiber bundle as a buffer, which means that cracks are conducted through the fiber bundles [49].

As described before, several reports describe the positioning of the fiber bundles at the cervical area of the construction as the theoretical optimal position, because of the tensile stress developing under loading [27-29]. To reach this, one should take the design of the construction into account, specifically at the weak connector area. However, it can be questioned if the theoretically optimal position can be achieved in a clinical situation. In the anterior area for example, the limited inter occlusal space in relation to non-invasive tooth preparation and the demand for an acceptable esthetic result must be taken into account and can complicate an optimal design.

One of the drawbacks to use FRC material is the insufficient knowledge of the framework design. The design influences the mechanical behavior of a prosthetic appliance but at this moment there is no unambiguous guideline for optimal design of the connector and retainer. Depending on the location, various retainer types are applied, including full crown, inlay or box restorations, Maryland wings and combinations. Considering a tissue saving treatment, minimal invasive preparations are desired. However, material volume contributes to the strength and this pleads for the removal of tooth material. In many cases it will be necessary to create inter occlusal space for the construction and it is questioned if extra mechanical retention is desired, such as grooves or occlusal support (occlusal rest).
Most theories that have been researched are directed to the application of FRC FPDs in the posterior area. In the anterior area however, less variety in framework design is possible. This makes it more interesting to know if the framework design meets the

requirements, and whether creation of inter occlusal space (thus preparation) is necessary to achieve this.

Clinical research on FRC FPDs is still limited available. Considering the development of FRC materials it is imperative to gather the available information on the performance of FRC FPDs, to come to a higher level of knowledge about the performance of these constructions. The use of FRC material for tooth-replacing constructions is considered valid par excellence for the anterior region, because of the assumed higher risk of failure in the posterior region [50]. However, until now specific knowledge on the performance of anterior FRC FPDs is lacking. Knowledge on as well the clinical as laboratory performance of anterior constructions in specific, will contribute to a better understanding of the design of the construction and behavior. Questions arise, whether the mechanical properties can be influenced by the design of the construction.

Relevance and objectives of this thesis

The design of an FRC FPD in the anterior area needs some specific attention, before considering the technique a viable alternative to fixed conservative bridge constructions. For example the available inter occlusal space to create composite volume, the possibility to design the fiber framework with respect to the theoretical optimal position of the fibers, and the different direction of applied stress compared to the posterior area, are challenging.

This thesis focuses on the replacement of an anterior tooth with a fiber-reinforced adhesive fixed partial denture. The general objectives of the present thesis are to address this issue of the use of fiber reinforcement in composite tooth replacing constructions, to investigate the design and the need of tooth preparation for anterior FRC FPDs, and to investigate the clinical performance of these restorations in respect to posterior FPDs. The main questions in this respect are:

- Does the use of fiber-reinforced materials contribute to the *in vitro* performance of adhesive resin composite FPDs?
- Are resin-bonded FRC FPDs a viable alternative to metal resin-bonded FPDs as a (semi) permanent construction in the anterior region?

The following specific questions are posed:

- o Does fiber reinforcement has a beneficial effect on in vitro fracture resistance and elastic modulus of resin composite?

- What is the clinical performance of FRC FPDs, with respect to survival probability and failure modes?
- Is there a relation between FPD design and clinical performance and can risk areas for anterior FPDs be indicated?

Outline of the thesis

This thesis starts with a systematic literature review to review the current literature on in vitro tests of fiber-reinforced (FRC) composite beams. The study is directed to studies that followed criteria described in an International Standard to guarantee comparability. Restricting to three-point bending tests, the flexural strength and modulus data of the selected studies are collected. The differences in mean flexural strength and modulus between reinforced and unreinforced beams are analyzed (Chapter 2).

In Chapter 3 a structured literature review is described on the clinical studies on resin-bonded FRC fixed partial dentures (FPDs). Failure modes and survival data of the selected studies are collected. A meta-analysis is performed to construct an overall survival curve.

The long-term clinical outcome of 3-unit anterior FPDs with a minimal service time of 5 years is evaluated in Chapter 4. In this study design factors influencing the survival rate are analyzed. In particular differences in performance between FRC FPDs with or without additional retention form is analyzed. In Chapter 5 the clinical outcome of 3-unit posterior FPDs with a minimal service time of 4.5 years is evaluated, with an analysis on the type of FPD.

Development of a model that can be used for laboratory tests on anterior FRC FPDs is described in Chapter 6. In this study a case simulation concerning the failure mode of an anterior FRC FPD is performed, by load testing of a clinical set-up.

Finally, Chapter 7 discusses the findings of the different parts of this study in summary and the relations between the results, presents some conclusions and provides some suggestions for future research in this field.

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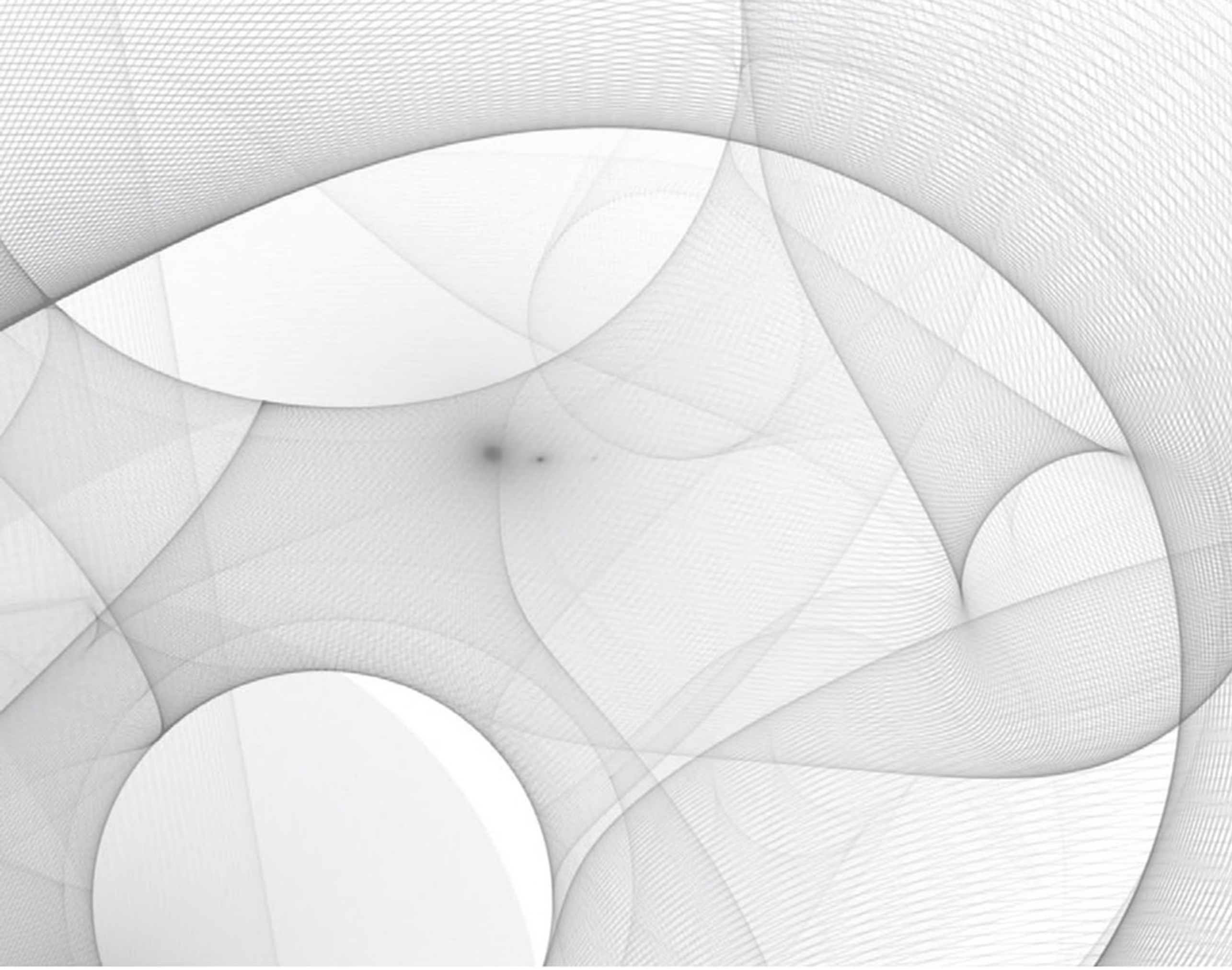

Chapter 2

Fiber-reinforced dental composites in beam testing

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Abstract

The purpose of this study was to systematically review current literature on in vitro tests of fiber-reinforced composite (FRC) beams, with regard to studies that followed criteria described in an International Standard. The reported reinforcing effects of various fibers on the flexural strength and elastic modulus of composite resin beams were analyzed.
Original, peer reviewed papers, selected using Medline from 1950 to 2007, on in vitro testing of FRC beams in comparison to non-reinforced composite beams. Also information from conference abstracts (IADR) was included.
With the keywords (fiber or fibre) and (resin or composite) and (fixed partial denture or FPD), the literature search revealed 1427 titles. Using this strategy a broad view of the clinical and non-clinical literature on fiber-reinforced FPDs was obtained. Restricting to three-point bending tests, seven articles and one abstract (out of 126) were included. Finally, the data of 363 composite beams were analyzed. The differences in mean flexural strength and/or modulus between reinforced and unreinforced beams were set out in a forest plot. Meta-regression analyses were performed (single and multiple regression models). Under specific conditions we have been able to show that fibers do reinforce resin composite beams. The flexural modulus not always seems to increase with polyethylene-reinforcement, even when fibers are located at the tensile side. Besides, fiber architecture (woven vs. unidirectional) seems to be more important than the type of fiber for flexural strength and flexural modulus.

Introduction

Fiber-reinforced composites (FRC) are generally being used in engineering applications. An important feature of composites is their ability to tailor the material until it meets the design requirements, which makes FRC highly suitable for a wide range of dental applications like removable dentures, root canal posts, provisional restorations and fixed partial dentures (FPDs) [1]. Although the use of the material is growing, the clinical behavior is not fully understood. A systematic review on scientific documentation of commercially available FRCs shows poor evidence to support their clinical use as an alternative for conventional materials [2].

Laboratory findings, however, point at a justified use of FRCs for specific applications. Generally, mechanical properties of FRC structures have been found to be superior to that of non-reinforced composites *in vitro* [3,4]. In high stress bearing areas a material with high flexural strength, high elastic modulus and low deformation as well as high impact and fatigue resistance is required. The mechanical behavior of FRCs has been researched extensively, but studies in this area have been conducted with many different materials and performed with different aims [4-7].

The mechanical behavior of FRC is complex compared to particulate-filler composite. Properties of FRCs can range from isotropic to anisotropic and the behavior of the construction is influenced by the volume, location and direction of the fibers [4, 8-10]. Laboratory investigations on FRC FPDs have favored the use of long continuous fibers located in the tensile area of the construction, with strands perpendicular to the direction of the applied load [1,9].

Three-point bending tests specifically simulate the loading of an overlying bridge construction, such as an FPD. Several studies have investigated properties like the flexural strength of FRC beams on the basis of these tests [11-13]. However, test conditions vary in construction design, span length and geometry of the beams, and loading speed and geometry of the loading apparatus. The same materials have been used with various amounts of incorporated fibers leading to different results [14,15]. A standard three-point bending test has been published by the International Standards Organization (for example ISO 4049). The ISO 4049 describes the preparation of a test specimen and the use of a universal test apparatus for bending tests on composite beams [16]. Several studies have been published using this standard test, but an overall view of the reinforcing effect of FRC in particulate composite beams is lacking.

It can be hypothesized that fiber-reinforcement increases both flexural strength and modulus of resin composite. Also it is expected that there is a difference in the effect of fiber-reinforcement on the mechanical properties between glass fibers or polyethylene fibers, the most commonly used fibers in dentistry, and other relevant characteristics. With respect to this hypothesis the objective of this study is to evaluate the *in vitro* reinforcing effects of fiber material on the flexural strength and elastic modulus of composite resin beams (FRC beams). A structured review is performed on the dental literature with regard to the criteria as described in the ISO test 4049.

Materials and methods

This review consisted of: literature search and selection, conference abstract search and selection, inclusion/exclusion of papers, extraction of data, and statistical analysis. The literature was searched with an electronic database (Medline) with the year limits 1950 to December 2006 as well as the Cochrane Library of Clinical Trials. Keywords used were (fiber or fibre) and (resin or composite or fixed partial denture or FPD). The electronic search was carried out to obtain a broad view on FRCs in fixed partial denture applications. The result of this search was used as a 'pool' to select studies on bending tests with composite beams. Two independent readers (CvH, CK) carried out a selection of the references found on the basis of abstracts as published in Medline. If no abstract was available in Medline the selection was done on the basis of the title of the article. The emphasis of this first step in the review procedure was on inclusion of references using the criteria shown in Table 1. For this step, and also for subsequent steps, disagreements were resolved by discussion.

The second selection step was carried out on the basis of the Materials and Methods sections of full text copies of the selected references by the two readers. *In vitro* studies in which fiber-reinforced composite beams were subject of the study were selected. Moreover, reference lists of the selected papers were hand-searched to identify additional *in vitro* studies on composite beams. Criteria as shown in Table 1 were used for inclusion. Additionally, the search for conference abstracts, specifically on in vitro beam testing, was carried out by the two independent readers, by searching the IADR abstracts on the website of the Journal of Dental Research, with year limits 2000-2007. Keywords used were (fiber, composite, strength, fixed partial denture and three-point bending test).

The selection procedure in step 3 specifically identified some predetermined test conditions as described in ISO 4049 (Table 1). From the Materials and Methods and Results sections of the articles data regarding test set-up and experimental results were extracted. Studies done with beam dimensions as described in ISO 4049 were selected (height 2 mm, width 2 mm, support distance 20 mm), in which the fiber orientation was longitudinal and for which flexural strength or flexural modulus was measured. Only studies that tested the properties of reinforced beams compared to an unreinforced control group (beams of composite resin only) were included.

Specimen from each study were allocated to groups (referred to as 'groups') according to the type of fiber (glass fiber or polyethylene (UHMWPE) fiber) and differentiation was made for specimen tested with the fiber location at tensile, compression, and neutral side, and vertically placed. Relevant characteristics were recorded and flexural modulus and flexural strength data were extracted.

Statistics

Cohen's kappa coefficient was used as a measure of agreement between the two readers in step 1 and 2 of the selection procedure. For step 3 and data extraction, selection was expected to be clear and was carried out by one observer. In case of doubt the second observer was consulted.

The (absolute) difference in mean flexural modulus (ΔFM) and/or flexural strength (ΔFS) between reinforced and unreinforced beams per study was assessed. Most of the studies provided statistical tests, however, statistics were not always directed towards this comparisons. A secondary analysis of the reported mean values in strength and modulus was performed to construct Δs and their 95%-intervals by (re) calculating the t-values, providing insight into the level of significance (P-values). The following formula was used:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{(S.D._1^2 + S.D._2^2)/n}}$$

Meta-regression was performed with a fixed effect multiple regression model to establish the relations between flexural strength or flexural modulus and relevant test variables. Dependent variables were ΔFM and ΔFS. Independent variables were 'type

Table 1 Review procedure

Step		Criteria	Information source
1	Include	- *fiber-reinforced FPDs as a subject (clinical study, in-vitro study, follow-up study)* - *material research on fiber-reinforced composite in which 3-pointbending tests or bar-shaped specimen were used* - *inclusion when doubt*	Abstract, Title
	Exclude	- *no dentistry* - *descriptive studies (description of technique (manual), case report, clinical report, reviews)* - *post or dowel* - *provisional restoration* - *denture base resin/PMMA*	
2	Include	- *in-vitro studies on FRC beams*	Materials and Methods
	Exclude	- *in-vivo studies* - *in-vitro studies with anatomically designed specimen* - *in-vitro studies testing shear bond strength* - *finite element studies*	
3	Include	- *unreinforced control group is used* - *specimen dimensions 2x2 mm, support distance 20mm* - *longitudinal fibers* - *flexural modulus or flexural strength is measured*	Materials and Methods, Results
	Exclude	-*dynamic testing*	

of fiber' (glass vs. polyethylene), 'fiber location' (tensile vs. non-tensile side), 'fiber architecture' (woven vs. unidirectional), ageing (water storage vs. dry storage) and 'preimpregnation' (yes vs. no). Interdependency between variables was checked in cross tables. The influence of each independent variable on the outcome was checked with a regression model. After that, a model was build using all independent variables. In the models studies were weighted using the inverse variant method, i.e. each study was given a weight reciprocal to the standard error.

Results

A total of 1427 titles were identified through the searching of Medline. After the first selection step, 101 articles remained and 1326 were excluded. Search for the Cochrane Library of Clinical trials did not reveal further relevant papers. Complete agreement was seen for 1406 articles, and consensus was reached in 21 cases (inter-reader agreement $\kappa = .89\ (\pm .02)$). In the second step 33 papers were related to *in vitro* studies on bar-shaped specimen (inter-reader agreement $\kappa = 1.00$). The handsearch of the reference lists of these 33 papers did not reveal any additional references. Seven papers met the inclusion criteria, and 26 papers were excluded in step 3 (Table 2).

The searching for conference abstracts revealed 126 abstracts. On the basis of the inclusion criteria in step 3, one abstract could be included for further analysis.

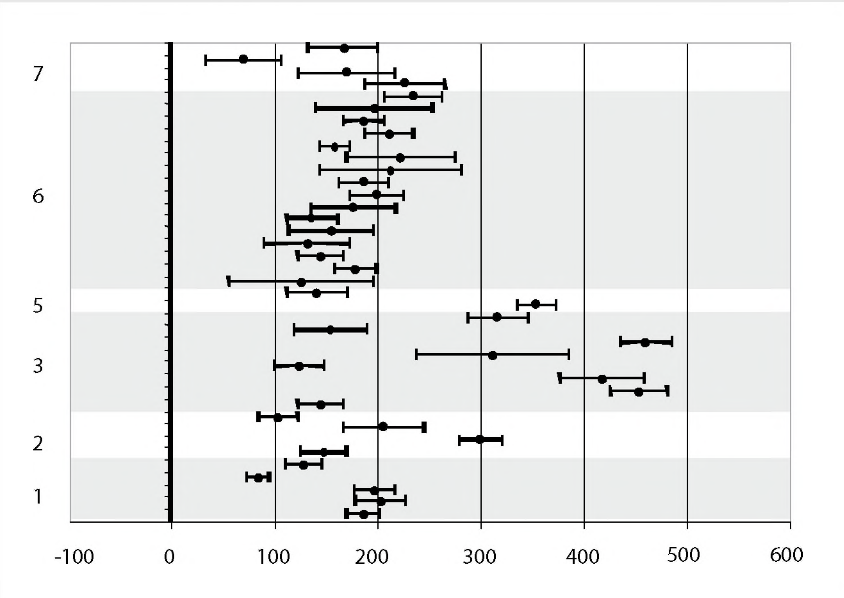
Table 2 Excluded and included in step 3

Excluded studies	Reason for exclusion
Eckrote et al [17], Nakamura et al [11], Chong et al [18], Viguie et al [12], Behr et al [19], Chong et al [13], Bouillaguet et al [7], Lastumaki et al [20], Chai et al [21], Chai et al [22], Fuji et al [23], Behr et al [24], Dyer et al [25], Lassila et al [26], Gohring et al [27], Alander et al [14], Alander et al [28], Drummond et al [29]	Studies without unreinforced control group
Kilfoil et al [30], Chong et al [18], Viguie et al [12], Behr et al [19], Chong et al [13], Fuji et al [23], Behr et al [24], Drummond et al [29], Ellakwa et al [31], Pereira et al [32], Xu et al [6]	Studies with specimen dimensions other than 2x2 mm, support distance 20 mm.
Alander et al [28], Eckrote et al [17]	Flexural strength or flexural modulus is not measured
Suzuki et al [3]	No longitudinal fibers
Bae et al [33]	Dynamic testing
Included studies	
1= Bae JM et al, 2001 [34], 2= Ellakwa A et al, 2002 [35], 3= Lassila LVJ et al, 2004 [36], 4= Anagnostou M et al, 2006 [37] *(conference abstract)*, 5= Garoushi SK et al, 2006 [38], 6= Ellakwa A et al, 2001 [15], 7= Ellakwa A et al, 2001 [5], 8= Dyer SR et al, 2005 [4]	

The extracted data of the included papers and abstract are in Tables 3 and 4. Results are grouped on the basis of the type of fiber and resin composite of the samples. The results of reinforced and unreinforced beams are shown in a horizontal comparison with the re-calculated P-value. Flexural strength data for FRC groups with fibers at the tensile side vary between 185 MPa and 577 MPa, and between 176 MPa and 585 MPa for groups with different fiber locations. Flexural modulus data for FRC groups with fibers at tensile side vary between 2 GPa and 15 Gpa, and between 8 GPa and 16 GPa for groups with different fiber locations. Significant differences between unreinforced and reinforced composite beams are colored in grayscale.

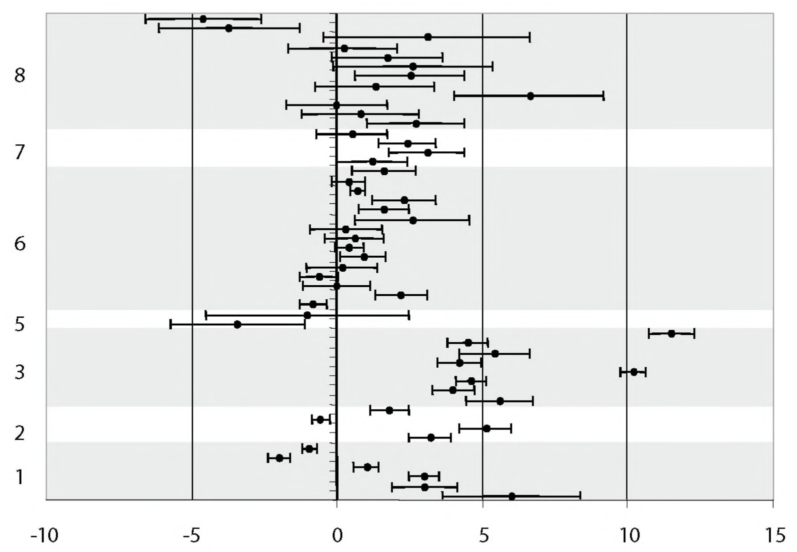
Forest plots of ΔFS and ΔFM and their 95%-intervals are presented in Figures 1 and 2. Only results that were expressed in the most common denominators (GPa and MPa resp.) are shown. As calculated from Tables 3 and 4 all ΔFS values differ from 0. On average a 100-200 MPa increase in FS is obtained by fiber incorporation. With ΔFM the

Figure 1 Forest plot of ΔFS and 95% intervals for all groups with FS measured in MPa



Positive values indicate an increase in FS by fiber incorporation. Numbers on the vertical axe refer to the included studies as presented in table 2

Figure 2 Forest plot of ΔFM and 95% intervals for all groups with FM measured in GPa



Positive values indicate an increase in FM by fiber incorporation. Numbers on the vertical axe refer to the included studies as presented in table 2

effect of fiber incorporation into the composite beam ranges from negative to positive. In 20 out of 34 (59%) FRC groups with fibers at the tensile side of the beam ΔFM is negative or no significant difference in FM with the unreinforced composite group was found (Table 3). In FRC groups with fibers at a different location, it appeared that for 35% and 47% of the groups respectively there is no significant difference, or even decrease, in FS and FM compared to the unreinforced composite group (Table 4).

Residuals of the results of Study 5 substantially differed from the other studies. To predict the influence of independent variables on the effect of fiber-reinforcement, this study could not be used in the meta-regression and was excluded in subsequent meta-regression models. Furthermore, some variables were strongly interdependent, since not all possible combinations of variables could be found in the studies (e.g. preimpregnated polyethylene fibers were not used in any study or do not exist). However, collinearity was not found between the variables. Single regression models of each independent variable on FS or FM are in Table 5a. The regression coefficient is

Table 3 Flexural strength (FS) in MPa and flexural modulus (FM) in GPa for all groups with fiber location at tensile side. Numbers (#) refer to the included studies as presented in Table 2

				Unreinforced composite		FRC		P value	Unreinforced composite		FRC		P value
#	**Fiber**	**Composite brand**	**n**	FS	SD	FS	SD		FM	SD	FM	SD	
Glass fiber brand													
1	FibreKor[a]	Sculpture Body	5	109.0	9.0	296.0	16.0	0.00	9.0	0.9	15.0	2.5	0.00
	GlasSpan[a]	Aelitefil	5	104.0	17.0	308.0	22.0	0.00	8.0	0.4	11.0	1.2	0.00
	GlasSpan[a]	C&B Cement	5	96.0	5.0	293.0	21.0	0.00	6.0	0.3	9.0	0.5	0.00
	Vectris Frame[a]	Targis	5	119.0	11.0	203.0	7.0	0.00	8.0	0.4	9.0	0.3	0.00
2	Sticktech[a]	Artglass + Artglass liquid	10	82.7	12.8	383.6	31.2	0.00	6.2	0.5	9.4	1.0	0.00
	Sticktech[b]	Artglass + Kolor Plus liquid	10	68.1	12.6	274.4	62.1	0.00	3.6	0.6	8.7	1.3	0.00
3	Stick[c,f]	Sinfony Dentin	6	123.5	13.7	577.7	25.5	0.00	6.4	0.5	11.0	0.4	0.00
	Stick[d,f]	Sinfony Dentin	6	90.1	13.3	509.3	33.0	0.00	4.9	0.5	9.4	0.7	0.00
4	Splint it[a]	Simile	3	24.5**	4.7	55.8**	2.9	0.00	-	-	-	-	-
5	StickNet[e,f]	Z250	6	88	12	230	35	0.00	11.4	2.0	8	2	0.02
	StickNet[c,f]	Z250	6	128	15	254	85	0.00	17.0	3.4	16	2.6	0.58
8	Vectris Pontic[a]	Targis	6	0.1*	0.05	4.53*	0.89	0.00	8.7	2.0	11.4	0.4	0.01
	Vectris Frame[a]	Targis	6	0.1*	0.05	0.42*	0.19	0.00	8.7	2.0	9.5	1.5	0.45
Polyethylene fiber (UHMWPE) brand													
1	Ribbond[a]	Aelitefil	5	104.0	17.0	233.0	10.0	0.00	8.0	0.4	6.0	0.2	0.00
	Ribbond[a]	C&B Cement	5	96.0	5.0	244.0	24.0	0.00	6.0	0.3	5.0	0.2	0.00
2	Connect[a]	Artglass + Artglass liquid	10	82.7	12.8	185.6	26.9	0.00	6.2	0.5	5.6	0.3	0.00
	Connect[b]	Artglass + Kolor Plus liquid	10	68.1	12.6	212.8	32.0	0.00	3.6	0.6	5.4	0.9	0.00

4	Ribbond[a]	Simile	3	24.5**	4.7	57.4**	7.7	0.00	-	-	-	-	-
6	Connect[a]	Artglass	10	82.7	12.7	261.6	29.1	0.00	6.1	0.4	5.3	0.6	0.00
	Connect[b]	Artglass	10	68.0	12.6	212.8	32.0	0.00	3.2	1.2	5.4	0.8	0.00
	Connect[a]	Belleglas	10	109.7	15.9	242.1	64.5	0.00	8.3	1.0	8.3	1.5	1.00
	Connect[b]	Belleglas	10	80.6	28.2	235.3	59.1	0.00	9.2	0.7	8.6	0.8	0.09
	Connect[a]	Herculite XRV	10	102.7	11.6	239.2	37.8	0.00	7.6	1.5	7.8	1.2	0.81
	Connect[b]	Herculite XRV	10	88.5	24.2	265.3	60.5	0.00	7.2	1.0	8.1	0.7	0.03
	Connect[a]	Solidex	10	65.6	7.9	265.2	39.6	0.00	4.9	0.6	5.3	0.5	0.12
	Connect[b]	Solidex	10	69.8	12.6	257.8	35.5	0.00	5.2	0.6	5.8	1.5	0.26
	Connect[a]	Experimental composite I	5	107.7	18.6	320.7	74.5	0.00	8.0	1.3	8.3	0.5	0.64
	Connect[a]	Experimental composite II	5	95.6	25.1	319.1	52.8	0.00	7.6	1.1	10.2	1.9	0.03
	Connect[a]	Experimental composite III	5	98.1	11.2	257.3	11.9	0.00	5.5	0.3	7.1	0.9	0.00
	Connect[a]	Experimental composite IV	5	106.7	22.1	317.7	14.9	0.00	5.9	1.2	8.2	0.2	0.00
	Connect[a]	Exp comp, filler weight 40%	5	70.4	13.8	256.8	17.8	0.00	1.9	0.2	2.6	0.2	0.00
	Connect[a]	Exp comp, filler weight 60%	5	85.8	9.0	282.8	62.8	0.00	3.1	0.4	3.5	0.5	0.20
	Connect[a]	Exp comp, filler weight 80%	5	89.3	6.7	324.1	30.6	0.00	5.4	0.3	7.0	1.2	0.02
7	Connect[f]	Herculite XRV	10	78.8	25.1	305.5	57.9	0.00	7.6	1.6	8.8	1.1	0.07
	Connect[b]	Herculite XRV	10	106.1	27.5	276.5	68.4	0.00	6.2	1.4	9.3	1.5	0.00
8	Connect[a]	Belleglass HP	6	0.09*	0.04	1.46*	0.26	0.00	12.6	2.1	12.6	0.4	1.00

*= Mean toughness (MPa)
**= Fracture force (N)

(light grey) = sign. positive effect
(dark grey) = sign. negative effect

a= water storage ≤ 1 week, b= water storage > 1 week, c= cured with Liculite curing device, d= cured with VisioBeta curing device, e= cured with Optilux curing device, f= stored dry in air.

Table 4 Flexural strength (FS) in MPa and flexural modulus (FM) in GPa for all groups with fiber location away from tensile side. Numbers (#) refer to the included studies as presented in Table 2

					Unreinforced composite		FRC		P value	Unreinforced composite		FRC		P value
#	**Fiber**	**Fiber location**	**Composite**	**n**	FS	SD	FS	SD		FM	SD	FM	SD	
Glass fiber brand														
3	Stick[c,f]	Compression side	Sinfony Dentin	6	123.5	13.7	248.1	31.2	0.00	6.4	0.50	12.0	1.3	0.00
	Stick[c,f]	Neutral (middle)	Sinfony Dentin	6	123.5	13.7	435.9	48.6	0.00	6.4	0.50	10.4	0.7	0.00
	Stick[c,f]	Vertical parallel	Sinfony Dentin	6	123.5	13.7	585.4	88.5	0.00	6.4	0.50	16.6	0.2	0.00
	Stick[d,f]	Compression side	Sinfony Dentin	6	90.1	13.3	245.8	26.7	0.00	4.9	0.50	9.1	0.8	0.00
	Stick[d,f]	Neutral (middle)	Sinfony Dentin	6	90.1	13.3	408.4	41.9	0.00	4.9	0.50	10.3	1.4	0.00
	Stick[d,f]	Vertical parallel	Sinfony Dentin	6	90.1	13.3	445.6	19.3	0.00	4.9	0.50	16.4	0.8	0.00
8	Vectris Pontic[a]	Compression side	Targis	6	0.1*	0.05	0.07*	0.02	0.00	8.7	2.00	15.3	2.4	0.00
	Vectris Pontic[a]	Neutral (middle)	Targis	6	0.1*	0.05	2.4*	0.51	0.60	8.7	2.00	10.0	1.5	0.23
	Vectris Pontic[a]	Vertical parallel	Targis	6	0.1*	0.05	1.1*	0.23	0.01	8.7	2.00	11.2	1.1	0.02
	Vectris Frame[a]	Compression side	Targis	6	0.1*	0.05	0.08*	0.05	0.50	8.7	2.00	11.3	2.7	0.09
	Vectris Frame[a]	Neutral (middle)	Targis	6	0.1*	0.05	0.17*	0.14	0.28	8.7	2.00	10.4	1.2	0.11
	Vectris Frame[a]	Vertical parallel	Targis	6	0.1*	0.05	0.11*	0.06	0.76	8.7	2.00	8.9	1.1	0.83
Polyethylene fiber (UHMWPE) brand.														
7	Connect[f]	Away from tensile	Herculite XRV	10	106.1	27.5	176.1	51.6	0.00	6.2	1.40	8.6	0.7	0.00
	Connect[b]	Away from tensile	Herculite XRV	10	78.8	25.1	246.2	47.5	0.00	7.6	1.60	8.1	1.0	0.41
8	Connect[a]	Compression side	Belleglass HP	6	0.09*	0.04	0.10*	0.02	0.60	12.6	2.1	15.7	3.8	0.11
	Connect[a]	Neutral (middle)	Belleglass HP	6	0.09*	0.04	1.50*	1.12	0.01	12.6	2.1	8.9	2.1	0.01
	Connect[a]	Vertical parallel	Belleglass HP	6	0.09*	0.04	1.04*	0.1	0.00	12.6	2.1	8.0	1.2	0.00

*= Mean toughness (MPa)
a= water storage ≤ 1 week, b= water storage > 1 week, c= cured with Liculite curing device, d= cured with VisioBeta curing device, f= stored dry in air.

= sign. positive effect

= sign. negative effect

significant for each independent variable, for FS and FM, except for the variable 'location'. The model fit for the single regression model of FS is less than the FM model, as concluded from the relatively low R square values.

Because of great coherence between independent variables, a multiple regression model was indicated with all variables included (Table 5b). The increase of FS is strongly associated with the 'fiber architecture' and 'ageing'. Applying unidirectional glass fibers, which are not preimpregnated or aged, at the tensile side instead of polyethylene fibers adds 497 MPa to the strength of the FRC beam (total of coefficients: 181.9 (constant) +21.9+99.6+14+180). Applying polyethylene fibers that are aged, at the compression side of the beam adds 65 MPa to the strength of the FRC beam (total of coefficients: 181.9 (constant)-117.2). It can be concluded that for every combination of variables there is an increase of flexural strength.

Interaction was present between the effect of the 'type of fiber' and effect of 'fiber location', which implies that there is a strong interaction between both effects. For example, incorporation of polyethylene fibers at the compression side reduces the reinforcing effect, while glass fibers at the compression side increase the effect to FS and FM.

Flexural modulus is not increased by the incorporation of fibers per se (constant is .262, with a 95% confidence interval [-1.46; 5.18]). The increase of FM is associated with the 'type of fiber' and 'fiber architecture', but not significantly.

Table 5a Simple regression models for each independent variable for flexural strength and flexural modulus. Variables as appearing in the first column (PE=polyethylene). Garoushi et al, 2006 is excluded [38]

Flexural strength					
Independent variable	*Regression Coefficient*	*Standard Error*	*t Value*	*Probability Level*	R^2
Constant	164.75	17.78	9.27	0.00	0.189
Type of fiber (1=glass;0=PE)	79.31	27.79	2.85	0.01	
Constant	234.69	35.41	6.63	0.00	0.037
Location (1=tensile;0=non-tensile)	-45.53	39.02	-1.17	0.25	
Constant	161.14	13.82	11.66	0.00	0.406
Fiber architecture (1=uni;0=woven)	126.86	25.92	4.90	0.00	
Constant	168.24	16.78	10.02	0.00	0.198
Preimpregnation (1=yes;0=no)	84.08	28.60	2.94	0.01	
Constant	288.47	26.52	10.88	0.00	0.305
Ageing (1=yes;0=no)	-118.16	30.17	-3.92	0.00	
Flexural modulus					
Independent variable	*Regression Coefficient*	*Standard Error*	*t Value*	*Probability Level*	R^2
Constant	0.36	0.44	0.82	0.42	0.544
Type of fiber (1=glass;0=PE)	4.68	0.72	6.46	0.00	
Constant	6.245	0.91	6.90	0.00	0.429
Location (1=tensile;0=non-tensile)	-5.15	1.00	-5.13	0.00	
Constant	0.58	0.36	1.60	0.12	0.634
Fiber architecture (1=uni;0=woven)	5.48	0.70	7.79	0.00	
Constant	0.56	0.42	1.32	0.20	0.535
Preimpregnation (1=yes;0=no)	4.82	0.76	6.34	0.00	
Constant	5.87	0.72	8.13	0.00	0.515
Ageing (1=yes;0=no)	-5.07	0.83	-6.10	0.00	

Table 5b Multiple regression model for flexural strength and flexural modulus using the variables as appearing in the first column (PE=polyethylene). Garoushi et al, 2006 is excluded [38]

Flexural strength				
Independent variable	*Regression Coefficient*	*Standard Error*	*t Value*	*Probability Level*
Constant	181.86	56.98	3.19	0.00
Type of fiber (1=glass;0=PE)	21.90	77.72	0.28	0.78
Location (1=tensile;0=non-tensile)	99.55	57.59	1.73	0.09
Fiber architecture (1=uni;0=woven)	179.97	52.94	3.40	0.00
Preimpregnation (1=yes;0=no)	-116.06	59.26	-1.96	0.06
Type of fiber x Location	13.98	67.56	0.21	0.84
Ageing (1=yes;0=no)	-117.24	42.34	-2.77	0.01
R^2	**0.59**			
Flexural modulus				
Independent variable	*Regression Coefficient*	*Standard Error*	*t Value*	*Probability Level*
Constant	1.86	1.62	1.14	0.26
Type of fiber (1=glass;0=PE)	4.41	2.26	1.95	0.06
Location (1=tensile;0=non-tensile)	-0.88	1.70	-0.52	0.61
Fiber architecture (1=uni;0=woven)	3.07	1.75	1.76	0.09
Preimpregnation (1=yes;0=no)	-2.00	1.86	-1.08	0.29
Type of fiber x Location	-1.68	1.92	-0.87	0.39
Ageing (1=yes;0=no)	-0.71	1.24	-0.57	0.57
R^2	**0.74**			

Discussion

This study focused on the basic question whether the incorporation of fibers has an effect on the mechanical properties of resin composite. A three-point bending is a standard simulation test of a bridge construction that can be used as a model to determine fracture strength and elasticity. This specific test design is quite broadly used which aids the comparison and pooling of results of separate studies [16]. This excludes other test designs, for instance the nanoindentation test, that analyzes similar material characteristics but is rarely applied [39]. Despite the standard test design, loading conditions varied on a small number of aspects. For instance, the geometry of the loading stylus varied, but is supposed not to be an important factor that will change the outcome of the results dramatically.

A systematic review was conducted to search for literature on this topic, followed by a meta-analysis to combine the results of *in vitro* tests. Although these techniques are originally intended to analyze the literature on relevant questions in randomized clinical trials, their objectivity supports the important role that systematic reviews can play in evidence-based dentistry. Moreover, since standardization of laboratory tests is feasible to a high level, the comparison of laboratory results in a meta-analysis is very attractive.

The selection procedure started with a broad search strategy with FRC fixed partial dentures as central theme. This step could have been more focused, but we would not take the risk of excluding papers. Of 33 included laboratory studies, only 8 used a (randomized) controlled test set-up using both unreinforced and reinforced composite. The search for conference abstracts was less broad because the amount of information on the internet is restricted. However, besides the IADR website we also did a handsearch in abstract books of IADR and Dental Materials conferences, to preclude a lack in search strategy. Not included in the systematic review is the quality control of included papers. Criteria for quality control of randomized clinical trials and other types of clinical studies have been described extensively [40-42]. These criteria for quality control however, are hardly applicable to the current data and international consensus would be minimal.

Due to the controlled set-up of the included studies, differences regarding strength and elastic modulus between reinforced and unreinforced beams could be assessed. It was shown that fiber incorporation reinforces resin composite beams, but an effective increase of strength or modulus goes with specific limitations.

Because of great coherence between influencing factors, the final multiple regression model could not distinguish one single parameter that determined the behavior of the fiber reinforced beam. Additionally, the results of Study 5 [38] significantly deviate, although study design and set up seem to be comparable to the other studies. Unknown influence of the choice of materials may have lead to the reported results. Despite the exclusion for analyses, the less favorable results of this study need to be taken seriously

Of the included variables, the compatibility with a specific veneering resin composite could not be analyzed for its wide variation in applied brands. In most studies only a single fiber bundle of a custom brand was incorporated in the beam. The fiber volume in a bundle is not investigated. Yet, it is reported that an increase in fiber volume results in improvement of mechanical properties [14, 24]. Others showed that an increase in load bearing capacity is not necessarily caused by higher fiber volume, but merely depends on the strength of the resin matrix, the bonding between fibers and matrix and deterioration by water sorption of fibers and matrix [11, 19].

In the regression model the placement of fibers at the tensile side did not significantly increase the strength or modulus on its own. From technical sciences and also described in other laboratory studies it is suggested that placement of the fiber at the tensile side of the beam is the most efficient location for reinforcement [4, 5, 9, 36]. From the present results it is suggested that placement of fibers at the tensile side does not per se increase the strength when unidirectional glass fibers are used. Some results show that polyethylene fiber-reinforcement might even decrease the modulus. The overall regression model shows a relatively small increase in the modulus which result is in agreement with other studies [4, 15, 32, 34]. Furthermore, the influence of the fiber architecture was shown to be more important than that of the type of fiber, which suggests that the behavior of woven glass fibers is comparable to that of polyethylene fibers. However, the interdependency is clear, since standard manufacturer products were included and polyethylene fibers are not available in a unidirectional structure.

Even more challenging is that it is indicated by Ellakwa that the physical and chemical properties of composite dominates the modulus of the FRC and not the incorporation of fibers [15]. Moreover, it is suggested that the interfacial adhesion and the matching of the modulus between the fiber and overlying veneering composite plays an important role in the reinforcing effect of flexural modulus [33]. The present result also suggest that under particular circumstances, the influence of resin composite properties regarding fracture strength and elasticity is larger than that of fiber incorporation. Consequently fibers should only be used under specific conditions.

Ageing of the specimen in the studies seemed to be associated with differences in strength and modulus. Artificial ageing varied from storing in dry air to thermocycling for variable periods, while the testing environment was dry in some studies and wet in other studies. From the literature it is suggested that measurements should be preferably done in a wet environment [2]. If so, one should be aware of the influence to the results. Finally, in the three-point bending tests as selected in this review the load is applied only in one direction, which makes the reinforcing effect of unidirectional fibers superior. Practically, occlusal forces will have various directions. Therefore it is advocated to redirect the study design for testing an overlying bridge construction with clinically relevant applied forces and valid construction models.

Conclusions

Under specific conditions fibers do reinforce resin composite beams. The flexural modulus not always increases with polyethylene-reinforcement, even when fibers are located at the tensile side. Besides, fiber architecture (woven vs. unidirectional) seems to be more important than the type of fiber for flexural strength and flexural modulus.

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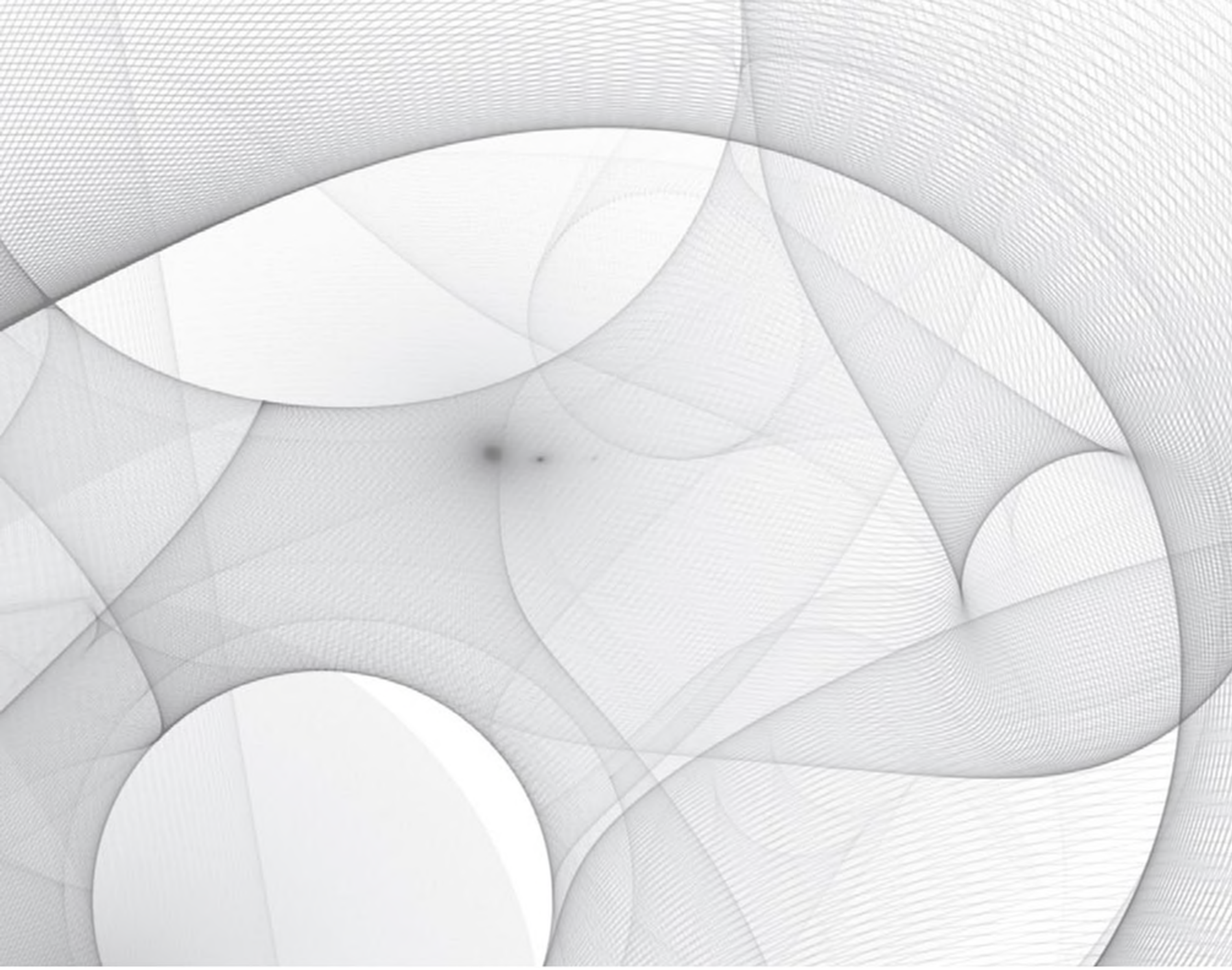

Chapter 3

Clinical studies of fiber-reinforced resin-bonded fixed partial dentures: a systematic review

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Abstract

In the past decade follow-up studies on fiber-reinforced composite fixed partial dentures (FRC FPDs) have been described. Combining the results of these studies to draw conclusions about the effectiveness of FRC FPDs is challenging. The objective of this systematic review was to obtain survival rates of FRC FPDs and to explore relationships between reported survivals and risk factors. In a literature-selection procedure 15 studies, reporting on 13 sets of patients, on the clinical performance of FRC FPDs were analyzed. Kaplan Meier estimate of the overall survival, based on the data from all sets of patients (n=435) was 72.3 (68.3-76.3)% at 4.5 years. Converted survival rates at 2 year follow-up showed substantial heterogeneity between studies. It was not possible to build a reliable regression model that indicated risk factors. The technical problems most commonly described were fracture of the FPD and delamination of the veneering composite.

Introduction

Resin-bonded fixed partial dentures (FPDs) have been in use for the last decades as an alternative for conventional FPDs when a tissue-saving treatment with relatively low costs is needed [1]. These constructions were originally made of metal combined with feldspatic ceramic. Currently, fiber-reinforced composites (FRCs) are used for various applications including FPDs. The advantages of FRCs are the tooth-colored material and the adhesive and tissue-saving properties of these constructions.

The use of FRCs for resin-bonded FPDs is advocated for their favorable elastic modulus compared to metal and better adhesion of the composite luting agent to the framework [2]. It is suggested that placement of the fiber at the tensile side of the beam is the most efficient location for reinforcement and that fiber type, fiber architecture and the interfacial adhesion between fiber and overlying composite seem to play an important role in the reinforcing effect [3-7]. It is also indicated that the physical and chemical properties of composite dominate the modulus of the FRC and not the incorporation of fibers. Yet, the benefit of fiber-reinforced constructions is questioned since the fiber framework is anisotropic and does not strengthen the construction in all directions in contrast to the metal framework [8]. However, in vitro research showed that fiber-reinforcement increases the fracture strength of resin composite to a level that justifies the clinical use of the material in unsupported applications [7, 9-11].

Clinical results should provide insight into the applications and restrictions of FRC FPDs. Indeed clinical data on fiber-reinforced FPDs have been published over the last 5 years [12, 13]. However, most of the publications are case reports or case series [14, 15]. Long term clinical, and preferably prospective studies comparing FRC FPDs with conventional (resin-bonded) FPDs are lacking. In an overview of the literature on FRC FPDs it was concluded that there is still poor scientific evidence for advocating FRC FPDs as an alternative to conventional FPDs with crown retention [8]. The survival rates of observational studies vary widely, and the conclusions are sometimes conflicting. This can be explained by different study characteristics, different materials and different clinical procedures used in the studies. For example, type of retention varies between studies from complete crowns to surface retainers or combinations of these.

In their review paper, Jokstad et al. [8] concluded that data on clinical behavior of FRC FPDs were too 'thin' to draw any conclusion. Since then, at least four reports of clinical studies have been published [13, 16-18] and the new information made it attractive to study the results of the individual studies and combine these to achieve an overall result using a meta-analytic approach.

This study aimed to gather and analyze the clinical data on FRC FPDs. The objective is to obtain survival rates of FRC FPDs and to explore relationships between reported survivals and risk factors.

Materials and methods

Medline (WebSPIRS 5.12) was searched for papers published from 1950 to October 2007 using the following keywords: (fiber or fibre) and (resin or composite) and (fixed partial denture or FPD). On the basis of titles and/or abstracts as published in Medline, two independent readers selected clinically relevant articles that described prospective or retrospective cohort studies. Only publications in English were selected. In-vitro studies were excluded. If the text indicated that the paper was a description of a technique, a case report or review, it was excluded. Reference lists of the selected papers were hand-searched to identify additional in vivo studies on FRC FPDs. Agreement between readers was determined using κ statistics and disagreements were resolved by discussion. This approach was applied in all steps of the study. In case of doubt, the reference was included.

From the selected references, full text copies were made and were screened independently by the two readers. In the articles information on the follow-up time, characteristics of the constructions, the survival rates and technical complications was retrieved. Data were extracted using a data extraction table.

Characteristics of the constructions included the design of the FPD, the location of the FPD and the choice of material. Concerning the bridge design, different retainer types (inlay, surface, crown retainer), different number of abutment teeth and different span distances were distinguished. As far as reported, the survival period for each FPD was extracted and the above characteristics of bridge design were extracted on an individual basis. Data were retrieved from tables, figures and the main text of the articles. If Kaplan Meier statistics were reported, events were depicted from the figures. If reported in the included studies, the number and types of technical complications and the number of failures were extracted. Replaced or rebonded FPDs were regarded as failed. FPD survival was defined as the FPD remaining in situ with or without modification during the observation period.

To construct an overall survival curve for the total number of FPDs from the selected studies, a database was made in which individual FPDs from each study were regarded as individual cases. The possibility of a regression analysis on different types and locations of FPDs was investigated. Time of failure was categorized in 6-months intervals and survival of the FPDs was assessed by the Kaplan Meier method (SPSS version 14.0, SPSS Inc., Chigaco, IL, USA).

Results

Included studies

A total of 1708 references were identified through the searching of Medline. After manual selection 15 clinical follow-up studies were included (Table 1). Complete agreement was seen for 1686 articles, and consensus was reached in 22 cases (inter-reader agreement $\kappa = 0.88$ ($\pm$ 0.03)). All studies were published within the past 15 yrs. Reference tracking did not reveal any additional paper. The majority of studies were conducted in institutional environments, such as university clinics. Except for one, all were observational studies. The one study used a controlled design to compare full-ceramic FPDs with FRC FPDs [19].

The Medline search showed that a few papers were follow-up reports of the same studies. Papers dealing with the same set of patients were combined and reference was made to the most recent publication of that study. In this way 13 sets of FPDs were identified.

The 13 sets of FPDs included a total of 435 FPDs with different types of framework design (Table 1). Forty-six percent of the FPDs were inlay-retained, 21% of the FPDs were surface-retained and 26% had a complete coverage crown as retainer. In some studies the retainer type was referred to as 'hybrid', which implies a combination of retainers, such as a crown at one abutment and a surface retainer at the other abutment. In eight studies it was reported that FPDs were retained at two abutment teeth and in one study most of the FPDs were cantilever bridges at one abutment [20]. Three studies were on FPDs directly made in the mouth; the rest of the studies reported on indirect (or laboratory) manufactured FPDs. Different materials were

Table 1 Study and FPD characteristics of the reviewed studies

Study	Yr of publication	Type of study	Sample Size	Procedure	Material	Mean number of abutments	Retainer type	Location (1)	Location (2)
Altieri et al. (21)	1994	Prospective	14	Indirect	Polycarbonate/ Prisma/PMMA*	2	Surface 14	Anterior 11 Posterior 3	Maxilla 9 Mandibula 5
Culy & Tyas (20)	1998	Prospective	27	Direct	FibreSpan/ Nulite F/V	1.2	Surface 27	Anterior 26 Posterior 1	Maxilla 27
Göhring et al. (30, 31)	1999;2002	Prospective	40	Indirect	Vectris Pontic/ Targis Dentin	2.1	Inlay[b]	Anterior 1 Posterior 39	Maxilla 21[1] Mandibula 19[1]
Vallittu et al. (2, 12)	2000;2004	Prospective	31†	Indirect	Stick(Net)/ Sinfony/ Vita Zeta	2.7	Inlay 4 Surface 23 Hybrid 4	Anterior 19 Posterior 12	Maxilla 17 Mandibula 14
Edelhoff et al. (19)	2001	Prospective	12	Indirect	Vectris Pontic/ Targis Dentin	2	Inlay 9 Hybrid 3	n.r.	n.r.
Freilich et al. (28)	2002	Prospective	39	Indirect #	FibreKor/ Sculpture	2	Inlay 17 Crown 22	Anterior 5 Posterior 28 Ant/post 6	n.r.
Monaco et al. (25)	2003	Prospective	41	Indirect ##	Vectris Pontic/ Targis Dentin	2	Inlay 41	Posterior 41	Maxilla 17 Mandibula 24
Bohlsen & Kern (22)	2003	Retrospective	83	Indirect	Vectris Pontic/ Targis Dentin	n.r.	Crown 83	n.r.	n.r.
Behr et al. (29)	2003	Prospective	22	Indirect	Vectris Pontic/ Targis Dentin	2	Inlay 17 Crown 5	n.r.	n.r.
Ayna & Çelenk (16)	2005	Prospective	28	Direct	Ribbond/ Clearfil APX	2	Inlay 28	Posterior 28	Maxilla 14 Mandibula 14
Göhring et al. (13)	2005	Prospective	36††	Indirect	Vectris Pontic/ Targis Dentin	2	Inlay 36[a]	Posterior 36	Maxilla 18 Mandibula 18
Unlu & Belli (17)	2006	Prospective	23	Direct	Ribbond/ Clearfil APX	2	Surface 23	Anterior 23	Maxilla 15 Mandibula 8
Monaco et al. (18)	2006	Prospective	39	Indirect	Vectris Pontic/ Targis Dentin	n.r.	Inlay 35 Hybrid 4	Posterior 39	Maxilla 17 Mandibula 22

n.r.: not reported, † Drop-out of 6 FPDs not included, †† 53 FPDs were made; the article selected one per patient for analysis, # 26 high volume FPDs and 13 low volume FPDs, ## 22 high volume FPDs and 19 low volume FPDs, * Acrylic resin tooth was used as pontic, [a] 19% of inlay retainers were > 3 surface inlays or crowns, [b] 16% of inlay retainers were > 3 surface inlays or crowns, [1] Calculated with data from table used. To date 7 out of 13 studies have been performed using the Targis/Vectris system. Two studies made a difference between low volume and high volume FPDs; high volume FPDs contained a larger amount of fiber material in the pontic area. Another study used two different resin composite cements [18]. One study used polycarbonate fibers and an acrylic tooth as pontic [21] and another study used non-resin luting materials (temporary cement, zinc phosphate or glass-ionomer cement) [22]. Because the fiber type, pontic material and luting materials differed substantially from other studies, it was decided to exclude these studies in further statistical analyses. These differentiations within the complete set led to the identification of 16 subgroups. Ten out of 13 studies reported on the location of the FPD; about 65% of the FPDs was placed in the posterior region.

Survival

Not all of the studies reported survival rates of the FPDs. Study data and survival rates are in Table 2. Observation periods varied between 10 mths and 5.7 yrs, while reported survival rates varied between 50% and 100%. If it appeared from the text that all FPDs were still in function without modifications after the observation period, a 100% survival rate was given. Most survival rates, however, were depicted from figures and tables. Figure 1 presents the combined survival curve up to 5 yr follow-up, which was derived from 11 studies with the stated variation in observational periods. Calculated survival rate at 4.5 yrs is 73.4 (69.4-77.4)%. Figure 2 shows a forest plot of the survival rates at 2 yr follow-up for each group of FPDs as far as it could be converted. The vertical line represents the mean survival rate. In this figure, heterogeneity between studies can be seen. Reported data could not be reduced to different types or locations of FPDs and therefore it was not possible to analyze data with a regression method.

Of the 435 FPDs, 88 FPDs failed within 5 yrs. The technical problem most commonly described is fracture or delamination of the veneering composite, which was reported in 10 studies. Occlusal wear of the material is described in 9 studies. For delamination as well as wear, difference is made between 'with' or 'without fiber exposure'; however, conclusions to this finding could not be found. Other problems reported were debonding of one retainer (5 studies), discoloration and fracture lines (cracks; 3 studies) (Table 3). Besides, some studies described problems as gingivitis, secondary caries, postoperative sensitivity, loss of vitality and reduced marginal integrity. These are regarded as minor problems.

Table 2 Data extracted from the reviewed studies. Number of failures are FPDs that needed to be replaced or rebonded. Presented survival rates are derived from the selected articles

Study	Group	Patient age (yrs)	Number of patients	Sample Size	Number of failures	Follow-up max. yrs.	Survival Rate	Drop-out %
Altieri et al. (21)	1	n.r.	12	14	6	2	±50%[###]	17%
Culy & Tyas (20)	2	15-58	26	27	2	0.9	n.r.	4%
Göhring et al. (30, 31)	3	19-66	29	40	5	1.5	n.r.	6%
Vallittu et al. (2, 12)	4	n.r.	31*	31	2	5.3	75%	22%
Edelhoff et al. (19)	5	n.r.	n.r.	12	0	1.9	100%[1]	n.r.
Freilich et al. (28)	6	n.r.	25	13[a]	10	4.6	62%[#]	0%
	7			26[b]			95%[#]	
Monaco et al. (25)	8	18-60	30	19[a]	2	4	86%	0%
	9			22[b]	0		86%	0%
Bohlsen & Kern (22)	10	24-75	39[†]	83***	43[$]	3	65.1%	10%
Behr et al. (29)	11	15-67	19[†]	22	0	4.4	55%	0%
Ayna & Çelenk (16)	12	~21.4	19	28	0	2	100%[1]	n.r.
Göhring et al. (13)	13	19-66	36	36	9[$]	5.7	73%/95%[##]	17%
Unlu & Belli (17)	14	15-35	23	23	5	3	100%[####]	0%
Monaco et al. (18)	15	18-60	39	19**	0	3	100%[####]	0%
	16			20**	4		89.4%[####]	0%

n.r.: not reported, a Low Volume FPDs, b High Volume FPDs, # Bruxers excluded, ## 73% for not delaminated and 95% for not debonded, ### At 12 months, #### At 24 months, † Total number of patients in the study, also treated with other types of restorations (i.e. crowns), * In the original analysis 29 FPDs were analyzed, excluding drop-outs, ** 19 FPDs cemented with Syntac Adhesive and 20 with Excite DSC adhesive, *** 28 FPDs cemented with temporary cement and 55 with Zinc Phosphate or glass-ionomer cement, $ Not clear whether all failures were absolute and replaced.
1 Concluded from text

Figure 1 Overall survival of the FRC FPDs included in the review (n=339, 2 studies excluded). Vertical bars indicate 95% confidence intervals

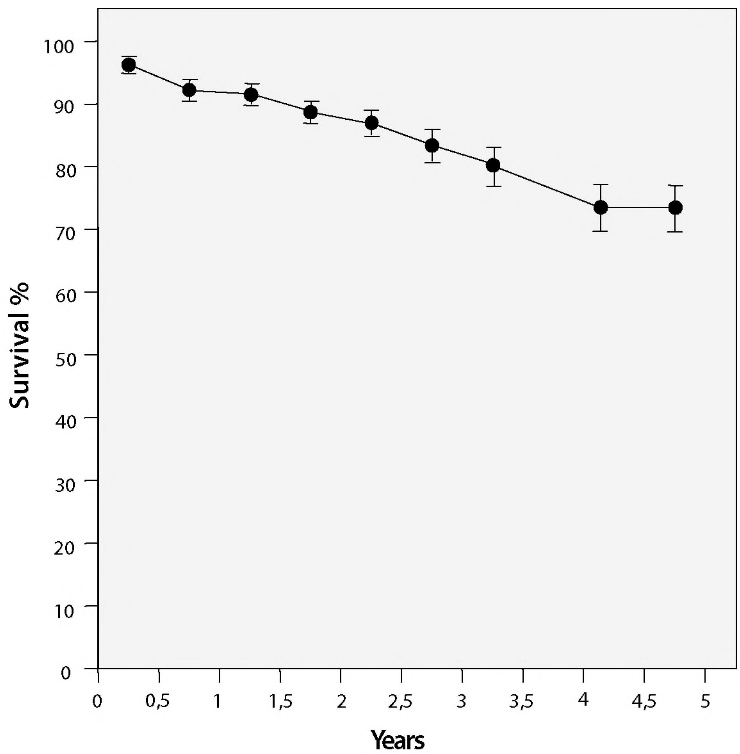

Figure 2 Survival probability by subgroups (group numbers from Table 1b) and calculated mean survival probability (derived from the reported data) at 2 yr follow-up. The size of dot marks is proportional to the group size and the diamond refers to the 95% confidence interval of the total

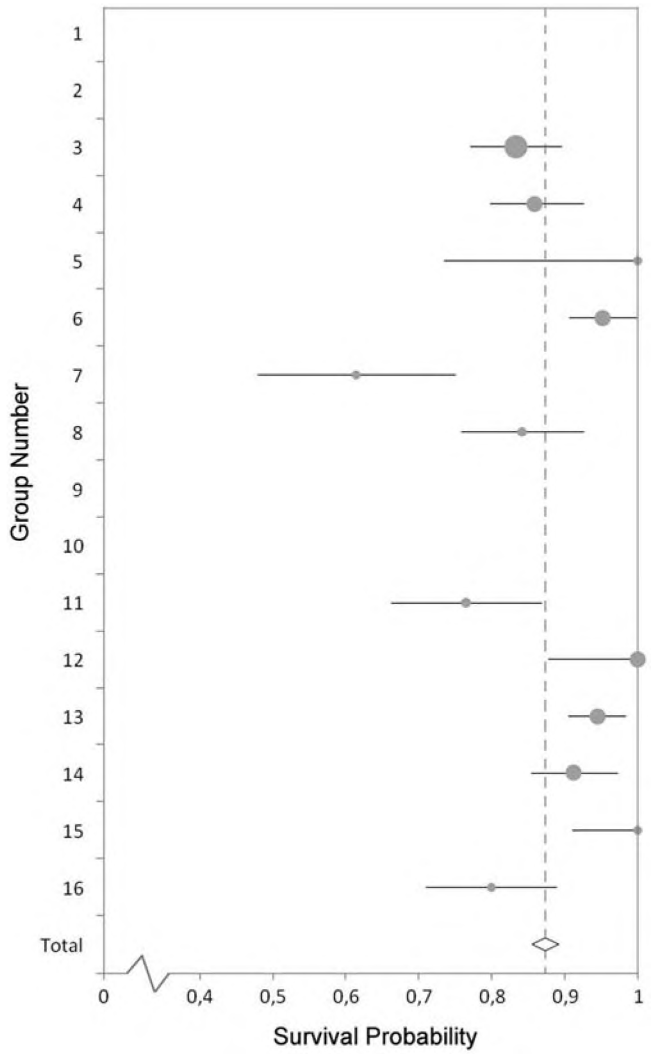

Table 3 Technical problems reported in the selected articles (not always regarded as failures in the studies)

Problem	Number of events reported	Mentioned as problem in article
Framework fracture	9	Culy & Tyas (20), Vallittu et al. (2, 12), Unlu & Belli (17)
Fracture of veneering composite (delamination)	9*	Behr et al. (29), Bohlsen & Kern (22), Culy & Tyas (20), Göhring et al. (30, 31), Freilich et al. (28), Altieri et al. (21)
Fracture of veneering composite with fiber exposure	21	Göhring et al. (30, 31), Göhring et al. (13), Freilich et al. (28), Monaco et al. (25)
Wear without fiber exposure	n.r.	Bohlsen & Kern (22), Göhring et al. (30, 31), Göhring et al. (13), Vallittu et al. (2, 12), Freilich et al. (28), Unlu & Belli (17)
Wear with fiber exposure	7**	Behr et al. (29), Culy & Tyas (20), Monaco et al. (18), Unlu & Belli (17)
Debonding	8**	Göhring et al. (30, 31) Göhring et al. (13), Monaco et al. (18), Vallittu et al. (2, 12)
Discoloration	n.r.	Behr et al. (29), Bohlsen & Kern (22), Göhring et al. (13)
Cracks (fracture lines)	n.r.	Göhring et al. (30, 31), Monaco et al. (18), Unlu & Belli (17)

* also mentioned in general in 2 other studies
** also mentioned in general in 1 other study
n.r.: not reported

Discussion

Clinical studies on FRC FPDs often fail to produce convincing evidence. The reasons for this include the difficulty of studying subjects under standardized circumstances and the limited size of the studies. Therefore, combining results of several smaller studies in a systematic review is a beneficial strategy. Systematic reviews are a tool for finding important and valid studies and have mainly been used to analyze Randomized Clinical Trials (RCTs) [23]. For this systematic review, only one controlled trial was available comparing conventional (resin-bonded) FPDs to FRC (resin-bonded) FPDs. In his overview on FRC literature Kelly [24] has indicated that for material-based treatment responses it is very difficult to define a control group and the inclusion and exclusion criteria should be customized to the purpose of the review.

The inclusion of studies in this review was therefore enlarged to all clinical trials, that were distinguished from case-reports. Lack of sample and study characteristics restricts the level of evidence. For instance, only 5 out of 13 studies described the patient selection criteria. Most studies excluded patients on criteria such as mobility of teeth, bruxers, or interproximal distance. Two studies reported that only patients who refused a treatment with dental implants received an FRC FPD, which probably is not a regular reflection of the average patient [18, 25].

Meta-analysis is the analytical part of a systematic review and finds its basis in the combination of results of independent studies. The idea is to recognize individual subjects of the studies as separate observations in the combined data set. If all observational units can be characterized, regression techniques can be applied to find relations between independent and dependent variables, for instance, FPD design and survival. Because of the lack of information on individual observations and study characteristics, it was not possible to apply regression methods. Some studies did not even report failure rates while other studies reported the failure rate and mode of failure without relation to design and location characteristics. Unfortunately, any conclusion about basic factors, such as the retention type or location of the FPD, cannot be drawn from the present data. Because of the lack of RCT protocols and fabrication differences in this field, it is suggested that clinical FRC literature appears insufficient for expert review [24]. However, we believe that analysis of the data of the included papers do contribute to a higher level of knowledge about the performance of FRC FPDs.

The majority of the studies showed a survival rate of 72% and higher after 2 to 5 yrs. A comparable treatment is the metal based resin-bonded FPDs which have been evaluated in various clinical studies. An analysis of 60 publications on resin-bonded bridges reported a survival rate of 74% after 4 yrs [26]. A difference was reported between survival rates of posterior resin-bonded bridges in the maxilla (81%) and the mandible (56%) after 2.5 yrs [27]. The majority of the laboratory made posterior FPDs in this review were inlay or crown retained, which cannot be compared to metal resin-bonded FPDs. To compare success rates of different studies, one must be sure that the outcome criteria assessment are consistent. It is clear that the included studies used different outcome criteria regarding success. Success can be defined as the survival of the FPD in its original form (without any modification), referred to as overall survival. In this view the presence of the construction (with or without any modification is regarded as functional survival rate [2, 12]. Variation between survival rates in different studies may have different sources including variation in patient selection, tooth preparation, choice of materials, luting cements and operator's experience. Two studies showed relatively low survival rates [21, 28]. The one is a study from 1994 that used polycarbonate fibers, which is a rarely used type of material and was therefore excluded from statistic analyses. The other study distinguished low and high fiber volume FPDs, and it showed that low volume FPDs had a significantly lower survival rate. This difference though, was not found in another study that discriminated low and high volume FPDs [25].

There is definitively a lack of detailed, standardized information on technical problems of FRC FPDs. Problems can be minor, such as discoloration or small chipping of composite, or they may be major, such as framework fracture or debonding that require replacement of the entire construction. In general, it can be concluded that the main reasons of failure of FRC FPDs are delamination of the veneering material, wear and debonding. Also discoloration has regularly been described as a problem [2, 12], while fracture of the fiber framework is rarely mentioned [25, 29]. The relationship between potential success factors and the overall survival rate is not explored until now, and a clinical guideline for the use of FRC FPDs is not yet achieved. Several authors consider a posterior location or long span distance as risk factors for FRC FPDs. Besides, it is not suggested to use FRC FPDs as a permanent restoration or long term solution [8, 19, 29, 30]. In this analysis convincing evidence to consider the former is not found. However, the need for well-designed randomized clinical trials is highlighted by this study.

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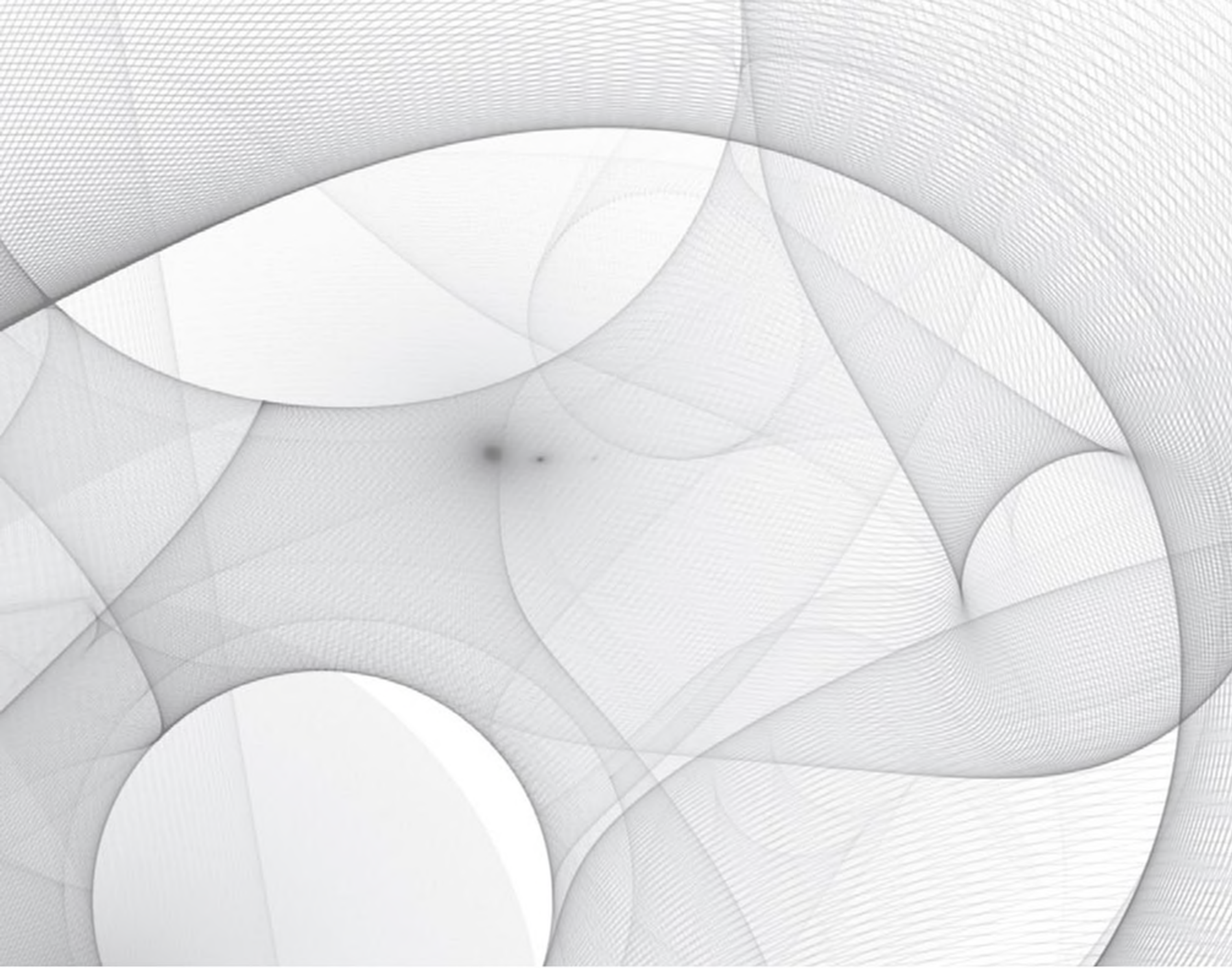

Chapter 4

Five-year survival of 3-unit fiber-reinforced composite fixed partial dentures in the anterior area

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Celeste C.M. van Heumen, Jan W.V. van Dijken, Johanna Tanner, Ronald Pikaar, Lippo V.J. Lassila, Nico H.J. Creugers, Pekka K. Vallittu, Cees M. Kreulen. Five year survival of 3-unit fiber-reinforced composite fixed partial dentures in the anterior area. *Dental Materials* 2009; 25: 820-827.

Abstract

The purpose of this clinical study was to evaluate the long-term outcome of 3-unit anterior fixed partial dentures (FPDs) made of fiber-reinforced resin composite (FRC), and to identify design factors influencing the survival rate. Fifty-two patients (26 females, 26 males) received 60 indirectly made FRC FPDs, using pre-impregnated unidirectional glass fibers, requiring manual wetting, as framework material. FPDs were surface (n=48) or hybrid (n=12) retained and mainly located in the upper jaw. Hybrid FPDs had a combination of retainers; i.e. crown at one and surface retention at the other abutment tooth. Surface FPDs were either purely adhesively retained (n=29) or with additional mechanical retention (n=19). Follow-up period was at minimum 5 years, with check-ups every 1-2 years. Six operators were involved, in three centers in the Netherlands, Finland and Sweden. Survival rates, including repairable defects of FPDs, and succes rates were determined. Kaplan-Meier survival rate at 5 years was 64% (SE 7%). For the level of success, values were 45 % (SE 7%) and the estimated median survival time 58 (SE 10.1) months. For surface FPDs, additional mechanical retention did not improve survival significantly. There was a trend towards better survival of surface FPDs over hybrid FPDs, but differences were not significant. Main failure modes were fracture of the FPD and delamination of veneering composite. A success rate of 45% and a survival rate of 64% after 5 years was found. Fracture of the framework and delamination are the most prevalent failure modes, especially for surface FPDs.

Introduction

The resin-bonded fixed partial denture (FPD) is a valid treatment option for replacement of missing teeth in selected cases. The main advantage of resin-bonded FPDs over crown retained FPDs is the preservation of dental hard tissues. Clinical survival rates of metal alloy resin-bonded FPDs have been reported to be 60% and higher after 10 years [1, 2]. An analysis of 60 publications on resin-bonded bridges reported a survival rate of 74% after 4 years [3].

Traditionally, metal alloy has been used as the material for the framework, but fiber-reinforced composite (FRC) is an alternative today. Inherent advantages are better adhesion of the composite luting agent to the framework, good esthetics and the physiological stiffness of the material. Moreover, restorative composite or fibers can be added to an already functioning FPD, enabling alterations and repair when needed. Various types of fibers and fiber products have been tested as reinforcing materials. Glass fibers are most often used because of their strength and their esthetic character compared to other fibers [4-6]. The development of fiber products available for dental use has led from plain fibers to pre-impregnated fibers and finally fully resin impregnated fibers. Mechanical properties of the materials have improved markedly along with the development. When fabricating FRC prostheses, reinforcement with long unidirectional fibers at the tensile side of the construction is recommended [7-11]. FRC FPDs can be fabricated either directly in the mouth or indirectly by a dental technician. When compared with the direct technique, the indirect technique offers ease of working, a higher degree of composite conversion rate and a better surface finish. Preparation design of abutment teeth in the anterior area is preferably a minimal invasive design (Maryland type) to preserve tooth material.

Although material properties of FRCs have been researched markedly [4, 5, 7, 12-14], clinical research is for the greater part restricted to case-series. From a review of clinical studies it is concluded that the performance of fiber-reinforced constructions cannot compete with FPDs with a metal framework yet [15]. In a direct comparison, it has been shown that 3- year survival rates of FRC FPDs were significantly lower than (resin-bonded) metal-ceramic FPDs [16]. Based on similar observations, it has been advocated to limit the indication for FRC FPDs to the anterior region, to short-span distances or to transitional restorations only [17-21]. However, two clinical studies have shown a substantial clinical performance of FRC FPDs with an overall survival rate of 75% after about 5 years, which can be higher than FPDs with a metal framework [22, 23].

In this study data were collected of FRC FPDs which were placed in three academic centers in the Netherlands, Sweden and Finland. The purpose was to evaluate the long-term clinical outcome of 3-unit anterior FPDs made of manually resin impregnated glass fiber-reinforced resin composite, and to identify design factors influencing the survival rate. In particular, difference in performance between FRC FPDs with or without additional retention form was analyzed. Service time was minimal 5 years.

Table 1 Distribution of anterior FRC FPDs (n=60)

Variable		N
Jaw	Maxilla Mandibula	57 3
Gender of the patient	Male Female	26 26
Pontic type	Central incisor Lateral incisor Canine	23 28 9
Operator	1 2 3 4 5 6	25 14 14 4 2 1
Academic Center	Nijmegen Turku Umeå	53 3 4
Material	Artglass Sinfony	53 7
Luting cement	Panavia Twinlook Compolute	17 36 7

Materials and methods

Study Design

Between April 1998 and September 2002, 52 patients (26 females, 26 males) of the departments of Oral Function and the Centre of Special Dental Care Radboud University Nijmegen (the Netherlands), the Institute of Dentistry University of Turku (Finland) and the Dental School Umeå (Sweden). Approval of the universities medical ethical committee was obtained (the joint commission on the ethics of the Turku University and the Turku University Central Hospital, resolution no. 264). Patients were treated with 60 indirect fiber-reinforced fixed partial dentures (FRC FPDs) in the anterior region. Informed consent was obtained. In most cases the patients were treated after referral by their own dentist. The patients' ages ranged from 13 to 64 years, with a mean age of 35 years. All FPDs replaced one missing tooth and two adjacent abutment teeth were used for retention, no cantilever bridges were involved. Forty-three patients received one FPD, five patients received two FRC FPDs. For two patients a new FPD was made after the first failed. For one patient this was repeated after a second failure, resulting in three subsequent FPDs. These FPDs were included as additional cases. Three FPDs were placed in the lower jaw and 57 in the upper jaw. The characteristics of the treated dentitions and FPDs are presented in Table 1. Patients were free of extensive periodontal disease and most of them had complete dental arches (except the missing tooth). X-rays to exclude periapical disease and loss of periodontal support of the abutment teeth were available.

We aimed for a minimal tooth preparation design and therefore most FPDs included surface retainers (Maryland wing design) but also inlay or onlay retainers in first premolars or complete coverage crowns were made (Table 2). In cases that used a combination of different retainer types, the type of FPD is referred to as 'hybrid' retained, for example, an inlay retainer in one abutment tooth and a surface retainer at the other. FPDs with surface retainers at both sides are referred to as 'surface' retained. Surface retainers can be divided in two groups: (1) retainers that are simply based on the adhesive interface enamel-composite luting cement; or (2) retainers additionally provided with a retention form being approximal grooves and an occlusal rest. Preparation forms were referred to as 'no preparation' (adhesive retention), 'retention' (rests and grooves), or 'preparation' (crown/inlay/onlay preparation) (Table 2). When for example one abutment-site was labeled as 'no preparation' and the other as 'preparation', the overall label was 'preparation'. Allocation of additional retention was based on the preference of the operator.

Table 2 Distribution of surface retained and hybrid retained FPDs (n=60)

Type of FPD	No preparation	Retention	Preparation	
Surface retained	29	19	0	48
Hybrid retained	0	3	9	12

Restorations

Treatment was performed by 6 experienced dentists, with adequate skills in adhesive techniques, according to a clinical protocol. Treatment was performed during two treatment sessions: (1) tooth preparation, impressions, and if necessary, provisional restorations; and (2) try-in, placement of the FPD and finishing.

In case of occlusal contact the palatal surface was ground to provide enough interocclusal space resulting in a complete surface to be used as a retainer site. Pre-existing restorations were removed and their cavity preparations were used as abutment preparations. If necessary, resin composite was applied in order to provide parallel cavity walls. If proximal grooves were made the positioning of the FPD was directed by their presence. In several cases an optimal approximal contact between abutment teeth and pontic was provided by preparing guiding planes. If no grooves were made, a palatal positioning direction was possible without the need to include guiding planes. After tooth preparation, impressions were made with a polyvinyl siloxane material. In several cases no temporary adhesive restoration was required, since a removable acrylic prostheses was available. If present, cavities were protected with a provisional filling material for the period of the laboratory procedure. Adhesive provisional restorations consisted of a pontic of an acrylic tooth, or an all-composite tooth, or a crown of an extracted tooth, which was retained to the abutment teeth with composite. Retention was mainly created by using the undercut cervical areas.
FPDs were made in dental laboratories on a full arch stone cast which was isolated with separating agent. The fiber framework consisted of manual resin wetting requiring unidirectional pre-impregnated glass fiber bundles (StickTM; StickTech Ltd., Finland). Each bundle consists of about 4000 glass fibers, with a diameter of 17 µm, embedded in a PMMA/BisGMA matrix. A bidirectional fiber mat (fiber diameter 10 µm) was used for additional reinforcement of the retainers (Sticknet; StickTech Ltd., Finland). Glass fiber reinforcements were manually impregnated with BisGMA-TEGDMA based light polymerizing monomer resin (Stick Resin; StickTech Ltd., Finland) to form

a PMMA-dimethacrylate inter-polymer network (IPN) (24) before use. Before the fibers were placed on the cast, a thin layer of flowable composite was applied at the retainer area. After light polymerization, the framework was veneered with composite resin (in Nijmegen: Artglass (Hereaus Kulzer, Germany), in Turku and Umeå: Sinfony (3M ESPE, Germany)). Sometimes an opaquer was used to aid in an esthetic restoration. The composite resin was built incrementally using a heat-light polymerization oven (in Nijmegen: Heraflash (Hereaus Kulzer, Germany), in Turku and Umeå: Visio Beta (3M ESPE, Germany)).

In the second treatment session, the provisional restoration was removed and the abutment teeth were cleaned with pumice. The fit of the FPD was checked using a silicon material (Fit Checker, GC, Japan); if needed the fit was adapted using diamond burs.

Rubberdam was applied in about 50% of the cases. Meanwhile, the bonding surface of the FPD was treated with monomer resin. The resin was left unpolymerized, shielded from light, for at least 3 minutes to allow the resin to penetrate and activate the IPN-phase of the polymethacrylate polymer matrix of the FRC framework. The bonding surface of the abutment teeth was acid-etched with 37% phosphoric acid gel for 20 seconds, rinsed and gently air dried for 5 seconds. FPDs were luted with a resin composite cement (in Nijmegen: Twinlook (Hereaus Kulzer, Germany) or Panavia (Kuraray, Japan), in Turku and Umeå: Compolute (3M ESPE, Germany)) according to the manufacturer's instructions. After removal of excess material, the resin composite cement was light cured for 20 seconds per surface. After polymerization, restoration margins were finished. Occlusion was adjusted with fine diamond-burs and the restoration was polished using rubbers and polishing discs. Patients received individual instructions to maintain plaque control.

Evaluation

Most of the patients were included in a care program that included 6 or 12 months general dental health check-ups, in the majority performed by their own dentist. Besides these check-ups, patients were advised to contact the dentist from the university clinic if any abnormality or event occurred concerning their FPD. For specific evaluation of the FRC FPDs, patients were invited for check-ups every 1-2 years. The performance of the restorations was evaluated by clinical examination. Caries and periodontal status, wear of the restoration, discoloration, fractures and dislodgements were recorded. After minimal 5 years, all patients whose records did not already indicate the failure or removal of the restoration were invited to participate in a clinical examination.

During the follow-up period, all interventions were recorded. Interventions may vary from finishing in case of chip fractures through repair by adding resin composite to renewal of the restoration. When records indicated interventions, the date and type of repair were recorded. If FPDs were repaired more than once, the first date of repair was used. The FPDs that could be rebonded after dislodgement, were rebonded using the same procedure as had been used originally.

Modes of failure were recorded as: 1) fracture of framework; 2) debonding one end; 3) dislodgement; 4) delamination; 5) combination of problems; 6) replacement. Fracture of the pontic, while the framework was still intact, was recorded as delamination.

Analysis

All restorations were included as individual cases with the following survival categorization:

Survival: FPDs were considered to have survived when no loss of retention or fracture was detected by the observers or patients. Also FPDs with small defects, such as wear or chipping were considered to have survived. No intervention was needed during service time.

Repaired: Interventions, such as polishing and finishing after chipping of small fragments of the veneering resin composite, repair of small delaminations with restorative resin composite, or adding fibers at the connector area of the fiber framework, were needed during follow-up. Also rebonding of FPD after dislodgement or debonding of one retainer was considered a repair.

Failure: An FPD was considered failed, when problems, such as fracture of the restoration, unrepairable delamination of the veneering resin composite, and combination of problems, that could not be repaired with the FPD in situ, occurred during follow-up.

The survival probability was analyzed at different levels: on the level of 'success' ($S_{success}$) and on the level of 'survival' ($S_{survival}$). Endpoints for the $S_{success}$ were the categories "failure" or "repaired" and were consequently recorded as censored. Endpoint for $S_{survival}$ was "failure". Data of drop-out patients were censored upon the last date that information of the FPD was available. Reasons for drop-out were traced.

Kaplan-Meier survival analyses were done for the complete group of FPDs and discriminated according to retainer type and preparation form. The 95% confidence intervals for survival probability at 5 years were calculated. Correlations between variables were crosschecked and possibilities for Cox regression analyses were researched, but appeared to be irrelevant. The analyses were performed with SPSS version 14.0 (SPSS Inc., Chigaco, IL, USA).

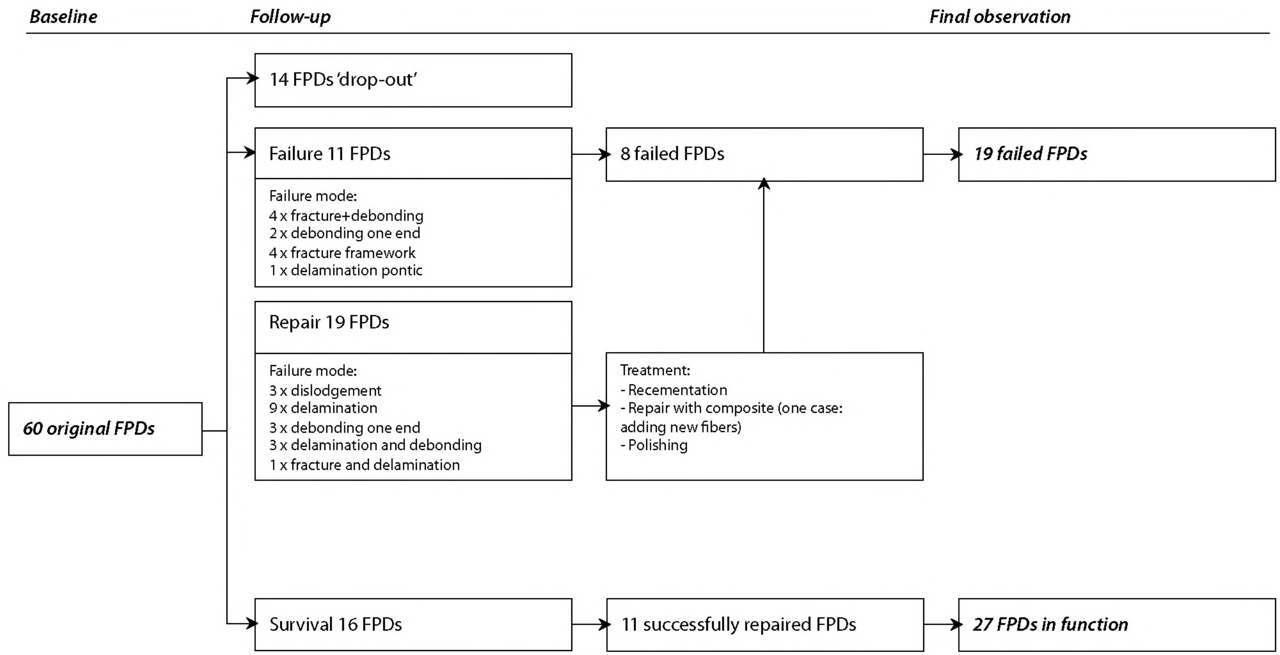
Results

The lifecycle of the FRC FPDs included in this study is shown in Figure 1. During the follow-up period 14 FPDs were lost to follow-up (22%). These drop-out patients could not be contacted or were not able to participate in follow-up examination mostly because of travel distance. One of the restorations was replaced with an implant-supported crown without being registered as failure and one was replaced with a full coverage FPD by another dentist for unknown reasons. Nineteen FPDs failed because of fracture, delamination or debonding, but were regarded as reparable by the operator. Reparable failures occurred at a mean follow-up of 27 months. The rebonded or repaired FPDs failed again in 8 cases within 3-19 months. Twelve failures were observed at a mean follow-up of 31 months.

The percentage distribution of failure modes is shown in Figure 2. For reparable failures delamination was the most commonly seen problem (47%). Fracture and combinations of problems were the main causes for total failure (both 33%). Fracture of the framework concerned in the majority of cases the connector area (Figure 3). Combined problems always included debonding and fracture of the surface retainers. Debonding mainly involved surface retained FPDs, with or without additional retention. One hybrid retained FPD, debonded after 2.8 years, was successfully replaced, while another one, debonded after 2.5 years, debonded and fractured again after 4.2 years. Focusing on failure modes of surface retained FPDs, it appeared that debonding occurred in 30% of the failed cases.

Overall survival curves for $S_{success}$ and $S_{survival}$ are shown in Figure 4. Kaplan Meier survival probability at 5 years was 45 % (SE 7%) for 'success' and 64% (SE 7%) for 'survival'. The estimated median survival time is 58 months (SE 10.1 months) for 'success'. Obviously, including repaired FPDs increases the survival rate.

Figure 1 Lifecycle of anterior FRC FPDs during the follow-up periode (5 - 9 yrs)



Survival rates for surface retained FPDs compared to hybrid retained FPDs are not significantly different for both $S_{success}$ and $S_{survival}$ (Figure 5; log rank test p>0.05). However, survival rates at 5 years seemed to be higher for surface retained FPDs ('success' 50% vs. 28%; 'survival' 68% vs. 52%). Focusing on surface retained FPDs it showed that the survival rates of $S_{success}$ without preparation was 45% (SE 10%), while this was 57% (SE 13%) for these FPDs with retention (Figure 6). For $S_{survival}$ rates were 66% (SE 10%) for FPDs without preparation and 71% (SE 12%) when retention was used. These differences in survival percentages were not statistically different (p>0.05). The survival plots for FPDs with and without retention are quite congruent.
Interaction between independent variables such as operator, patient age, preparation, type of FPD and luting cement, hampers a valid regression analysis.

Figure 2 Failure mode in categories at $S_{success}$ and $S_{survival}$

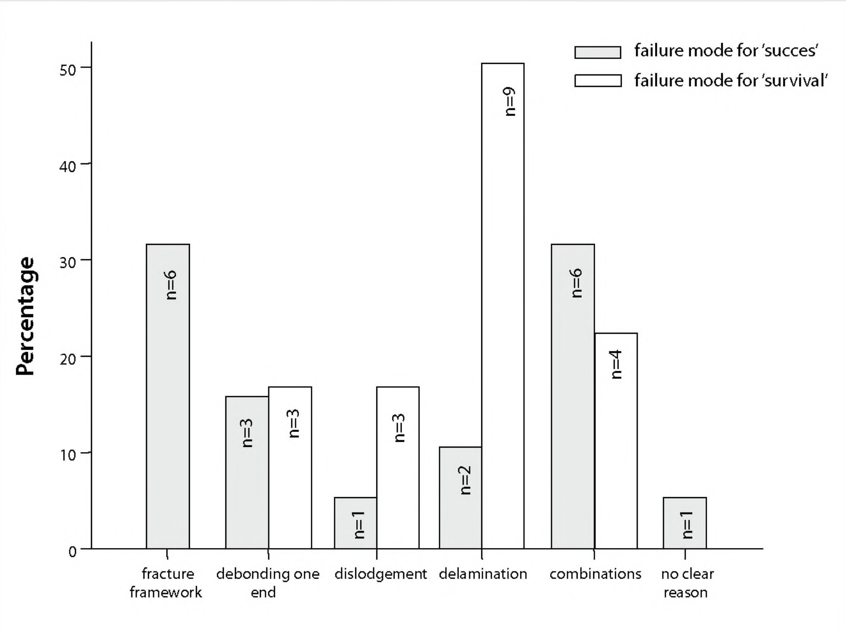
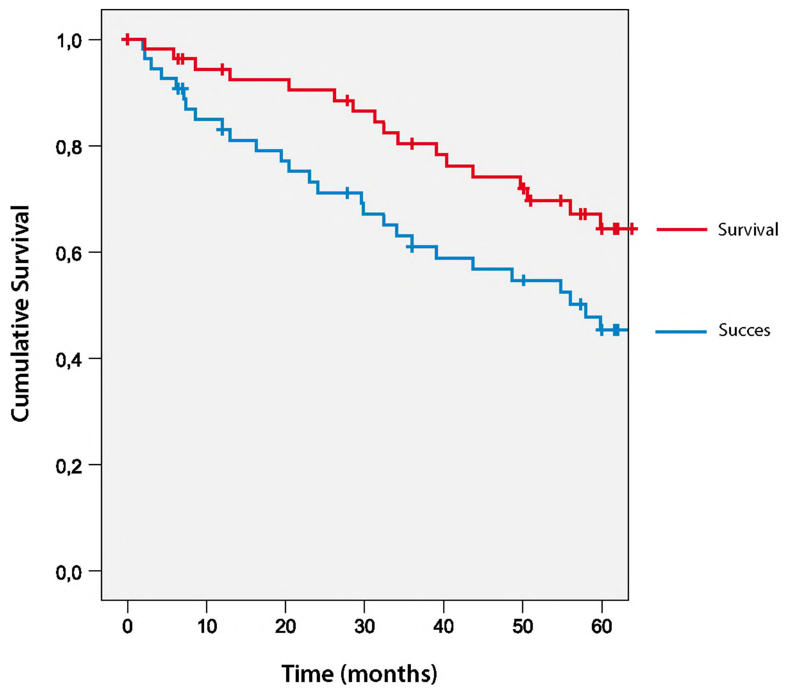


Figure 3 Failure of a surface retained FPD. Connector area is fractured, after delamination/wear

Discussion

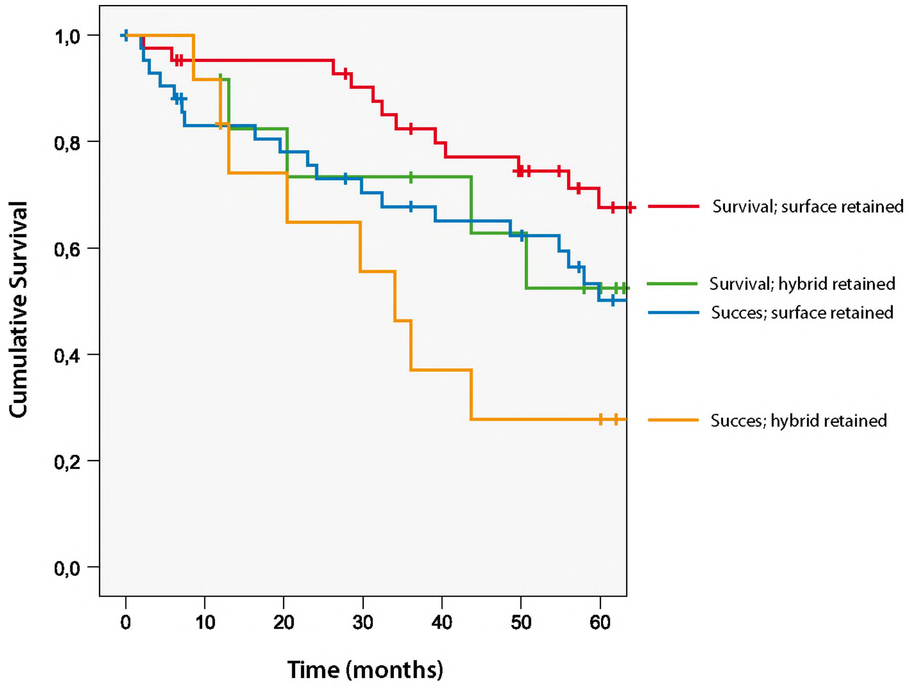
This study reports on indirect anterior FRC FPDs. To our knowledge, no long-term results have been published so far. The 45% success rate after 5 years in this study is a modest result for restorations that have a permanent character. The result is better compared to the 50% success rate for comparable restorations found earlier after just 12 months [28]. Considering the 64% survival rate after repair of the present restorations, the result is nearly as good as the 75% survival rate for surface retained FPDs at a follow-up of approximately 60 months [27]. Compared to metal resin-bonded FPDs, with reported 5-year survival rates up to 87.7% [29], the attractive features of the FRC FPDs are the esthetic nature of the framework and the easier possibility of repair and adjustment of the construction. Delaminations of resin composite can be repaired relatively easily by adding material after appropriate preparation of the fractured surface. Repair may also include adding fibers in situ, but the structural strength may be at risk. The 5 years success and survival rates were clearly different, which implies that repair of the FPD is beneficial to restoration survival time.

Figure 4 Restoration survival probability as a function of time for FRC FPDs (n=60)

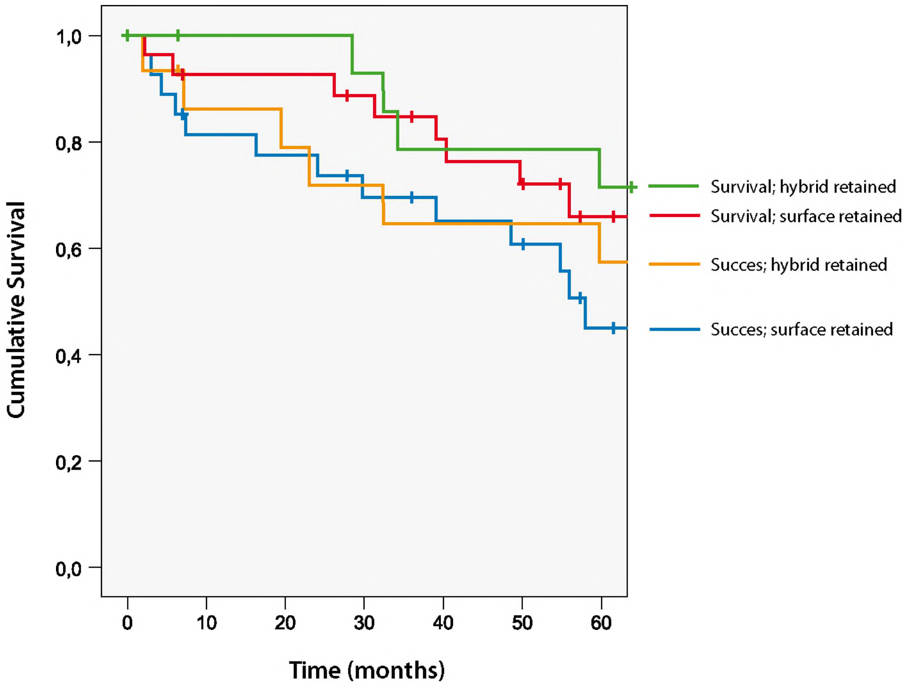


The laboratory fabricated FPDs of this study were made of partially pre-impregnated glass fiber bundles and were developed in the late 1990s. Of the three kinds of dental fiber products available today (plain, partially and fully resin impregnated fibers) the first two require manual impregnation of the fiber bundles by the operator. It is known that manual resin impregnation results in lower fiber fractions than what can be obtained by modern fully resin impregnated glass FRCs (30% vs. 65 wt%) and strength of the construction is related to the relative fiber quantity in the cross-section of the material [25, 26]. Accordingly, static flexural strength of manually impregnated FRCs range from 250 to 350 MPa, while the range is 750-1200 MPa for fully resin impregnated glass FRCs [27-29].

Figure 6 Restoration survival probability as a function of time for surface retained FPDs for 'no preparation' (n=29) and 'retention' (n=19)



The fabrication of FRC FPDs in this study consisted of a single longitudinal fiber bundle in the framework and additionally woven fibers in the retainer area. No supporting fibers for the pontic were added. Freilich et al. showed *in vivo* and Xie et al. *in vitro* that a higher quantity of fibers in the pontic prevents veneer delaminations in that area [23]. This may put our results into light regarding the most common reasons of failure, being delamination and frame fracture. Although those reasons are in agreement with others [27-29], adaptation of the framework design might improve performance of the FPDs. Recent data on FEM modeled FRC FPDs suggests ways to optimize the design and provide better support for the pontic with lower interfacial stress between veneer and fiber framework [30]. Furthermore, in bridge constructions the connector



areas have to resist the highest tensile and shear forces [31, 32]. Strengthening of this part of the construction may be obtained by changing preparation protocols and create more materials volume for the resin composite or fiber material.

This study was a mix of a prospective trial and a retrospective evaluation. Generally accepted limitations of retrospective studies, like their non-protocolized design, are not applicable to this study. Operators worked according to a clinical protocol and the restoration design was restricted to 3-unit FPDs. This study forms part of a trial including posterior FPDs. Unfortunately the sample proportions were not equally distributed between centers, being the major part of restorations made in Nijmegen. The laboratory procedures deviated on details. For example, the three clinical centers chose two different resin composite veneering materials which depended on their experience with the materials. It has been stated that resin materials with a higher elastic modulus may perform better under clinical conditions [33]. However, a comparison between used materials can not be made because of the difference in group sizes. The indications for tooth replacement in the study varied from a temporary solution in younger patients with multiple ageneses to (semi)permanent restorations to save costs, both biologically and financially. It can be anticipated that patient selection influences the results but it is not clear to what extent.

The detailed preparation design of the FPD abutment teeth varied. Surface and hybrid retained FPDs can be discerned, which is the consequence of the variation in the dental status of subjects. Hybrid retained FPDs include combinations of a surface retainer, an inlay or a crown. We did not observe a substantial difference in survival rates for surface and hybrid retained FPDs. This gives reasons to suppose that anterior FPDs with retainers that have inherent retentive capacity (inlay, crown) did not inevitably lead to better results compared to purely adhesive retained FPDs. Restricted to the surface retained FRC restorations, additional retention (grooves, rests) of the retainer hardly improved survival, but merely prevented debonding, since fracture of the framework and delamination was seen more often than with purely adhesive retention. It was shown that metal resin-bonded FPDs with approximal grooves were more retentive than without grooves (34). It is interesting to note that resin extensions (into grooves) of the FPDs, that technically cannot be fiber reinforced, did not show cohesive fracture.

Failures can be traced to several causes. Possible reasons for the observed failures are: (1) degradation of the luting agent, (2) disintegration of the interface between framework and veneering resin composite [35, 36], (3) fracture of thin connector areas and the low bulk retainers, (4) stress induced by dynamic occlusion, loading the FPD not perpendicular to the fiber direction. Since the adhesive surface of the FRCs was resin composite, one would expect debonding or dislodgement from the resin composite luting agent to be a minor problem. Despite we found debondings or dislodgements. To note, the predominant reason for failure of surface retained metallic resin-bonded FPDs is known to be debonding [37]. Wear was never recorded as a reason for failure or repair, although wear of resin composite was seen in several cases. It is possible, however, that delamination and wear are two phenomena that are hardly discernible. The surface retainer was in most instances only a thin layer of glass fibers embedded in resin composite and wear of the superficial layer exposes the fibers which increases risk of delamination or fracture.

Conclusions

The three unit anterior resin-bonded FRC FPDs in this study showed a clinical survival rate of 64% after 5 years. For indirect FRC FPDs with manually impregnated glass-fibers, fracture of the framework and delamination of veneering composite were the most prevalent failure modes, especially for surface retained FPDs.

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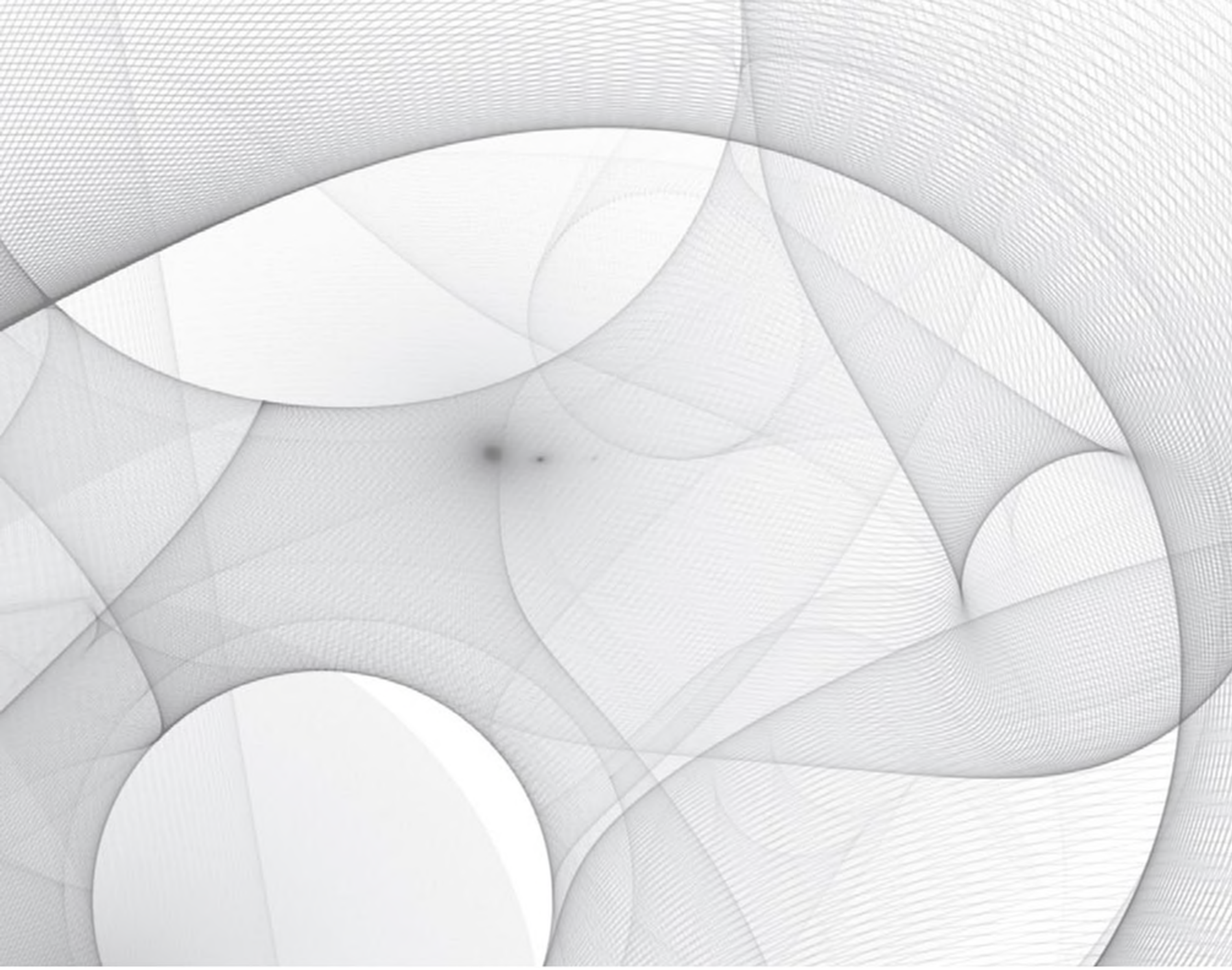

Chapter 5

Five-year survival of 3-unit fiber-reinforced composite fixed partial dentures in the posterior area

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Celeste C.M. van Heumen, Johanna Tanner, Jan W.V. van Dijken, Ronald Pikaar, Lippo V.J. Lassila, Nico H.J. Creugers, Pekka K. Vallittu, Cees M. Kreulen.
Five-year survival of 3-unit fiber-reinforced composite fixed partial dentures in the posterior area.
Dental Materials 2010; 26: 954-960.

Abstract

The purpose of this clinical study was to evaluate the long-term outcome of three-unit posterior fixed partial dentures (FPDs) made of fiber-reinforced resin composite (FRC), and to identify design factors influencing the survival rate. Seventy-seven patients (52 females, 25 males) received 96 indirectly made FRC FPDs, using pre-impregnated unidirectional glass-fibers, requiring manual wetting, as framework material. FPDs were surface (n=31) inlay (n=45) or hybrid (n=20) retained and mainly located in the upper jaw. Hybrid FPDs consisted of a wing retainer at canine and an inlay retainer at distal abutment tooth. Surface FPDs consisted of uplay and wing combinations. Follow-up period was at minimum 4.5 years, with check-ups at every 1-2 years. The study was carried out by 6 operators in three centers in the Netherlands, Finland and Sweden. Survival rates, including reparable defects of FPDs, and success rates were determined. Kaplan-Meier survival rate at 5 years was 71.2% (SE 4.8%) for success and 77.5% (SE 4.4%) for survival. Differences were not significantly different. Main failure modes were delamination and fracture of the FPD. Only FPDs with surface retainers showed debonding. A success rate of 71% and a survival rate of 78% after 5 years was found. Survival rates of inlay, hybrid and surface retained FPDs did not significantly differ.

Introduction

The fixed partial denture (FPD) is a treatment modality offering tooth tissue conservation together with lower treatment costs. In a recent meta-analysis, the resin bonded FPD fabricated with a metal framework showed an estimated survival rate of 87.7% after 5 years [1]. Complications like debonding of the framework from the luting cement were frequent and have been related to the unsatisfactory surface treatment of the metal alloy, due to difference in thermal expansion with regard to resin composite luting cements and the rigidity of the metal framework [2]. Moreover, esthetic considerations may be a drawback. It is expected that fiber reinforced composite (FRC) FPDs may provide an improved adhesive performance, because the material of the construction is similar to the luting material and FRC constructions are less rigid.

FRCs have recently been developed for dental applications and various types of fibers and fiber-products have been tested as reinforcing materials. Glass fibers are most often used because of their ability to withstand tensile stress and to prevent crack propagation in resin composite materials, and their esthetic character [3, 4]. Substantial improvements in flexural strength, fracture toughness and elastic modulus have been achieved in dental resin composites reinforced with fibers [5]. The development of fiber products available for dental use has led from plain fibers to pre-impregnated fibers and finally fully resin impregnated fibers.

The retainer designs of an FRC prosthesis can be either full-coverage or partial coverage types, depending on the condition and amount of remaining sound tissue of the abutment teeth. The freedom in design of the FPD allows a tooth-conserving preparation when the abutment teeth are unrestored or have modest restorations. Fibers in the bridge construction run from the retainer at one end to the other, are preferably located in the tension side of the bridge and are completely covered by resin composite material. In addition, an FRC FPD can be fabricated either directly in the mouth or indirectly by a dental technician.

Two systematic reviews of all commercially available FRC products without discrimination between type of retainers or fabrication technique have been published [6, 7]. In both studies a limited number of published clinical studies was found, all of relatively limited duration, and few of the reported commercial products demonstrated robust clinical documentation to support their use. Problems specifically associated with a commonly used system include fractures of the veneering composite [8-10], but also wear [8] and discoloration [10] have been observed. Consequently, there is a need for data on other systems, preferably based on trials of longer duration.

In a recent study we reported 5-year follow-up data of three-unit anterior FRC FPDs, made of manually resin impregnated glass-FRC, which were placed in three academic centers in Finland, the Netherlands and Sweden [11]. The purpose of the present study was to evaluate the long-term clinical outcome of three-unit FRC FPDs, but now applied in the posterior area. The FRC material was identical and all FPDs were indirectly made. Minimum service time was 4.5 years and design factors influencing survival were identified. Studies on metal resin-bonded FPDs showed lower survival rates in the posterior than in the anterior region, thus we expect that the survival rate of FRC FPDs shows the same difference.

Materials and methods

Between April 1998 and September 2002, 77 patients (52 females, 25 males) of the departments of Oral Function and the Centre of Special Dental Care of the Radboud University of Nijmegen (the Netherlands), the Institute of Dentistry University of Turku (Finland) and the Dental School Umeå (Sweden) were treated with 96 three-unit posterior indirect FRC FPDs. Approval of the university medical ethical committee was obtained (the joint commission on the ethics of the Turku University and the Turku University Central Hospital, resolution no 264). Informed consent was given for each patient. The patients' ages ranged from 12.4 to 77.5 years, with a mean age of 38.6 years. All FPDs replaced one missing tooth, which could be the first and second premolar or the first molar, and two adjacent abutment teeth were used for retention. No cantilever bridges were involved. Sixty-two patients received one FPD, 13 patients received 2 FPDs and 2 patients received 4 FPDs. Among these, it concerned an FPD that was made after the first failed in 4 cases and these FPDs were included as new cases. The characteristics of the dentitions of subjects and FPDs made are presented in Table 1. Patients were free of extensive periodontal disease and most of them had complete dental arches (except the missing tooth). X-rays to exclude periapical disease and loss of periodontal support of the abutment teeth were available.

We aimed for conservation of tooth tissue and the FPD designs used depended on the level of restoration of the individual abutment teeth. The retainer designs of the two abutment teeth made can be divided into three categories: (1) uplay and wing combinations (surface retained), (2) both inlay retainers (inlay retained), and (3) wing retainer at palatal side of canine, inlay at distal abutment tooth (hybrid FPD) (Figure 1). Wing retainers (or so-called Maryland design surface retainers) were always provided with occlusal support. This could be designed as a minimal inlay-box preparation or, if there was any interocclusal space, without removal of tooth material. Uplay retainers were designed as an occlusal 'wing'. In 12 cases the inlay retainer was provided with an additional wing at the buccal or lingual surface. The numbers of different FPD designs are described in Table 2. Types of FPD designs were not evenly distributed between the three centers, with most of the surface retained FPDs made in Nijmegen, whereas the material of Turku and Umeå was predominantly of the inlay-type.

Table 1 Distribution of posterior FRC FPDs (n=96)

Variable		N
Jaw	Maxilla Mandibula	51 45
Gender of the patient	Male Female	25 52
Pontic type	Premolar Molar	75 21
Operator	1 2 3 4 5 6	10 21 29 8 10 18
Academic Centre	Nijmegen Turku Umeå	60 28 8
Material	Artglass Sinfony	60 36
Luting cement	Panavia Twinlook Compolute Variolink	29 31 26 10

Figure 1 Type of FPD: A. Surface retained FPD with uplay retainers at both abutment teeth, B. Surface retained FPD with uplay retainer at distal abutment tooth and wing retainer at mesial abutment tooth, C. Hybrid retained FPD with inlay retainer at distal abutment tooth and wing retainer at mesial abutment tooth, D. Inlay retained FPD with inlay retainers at both abutment teeth

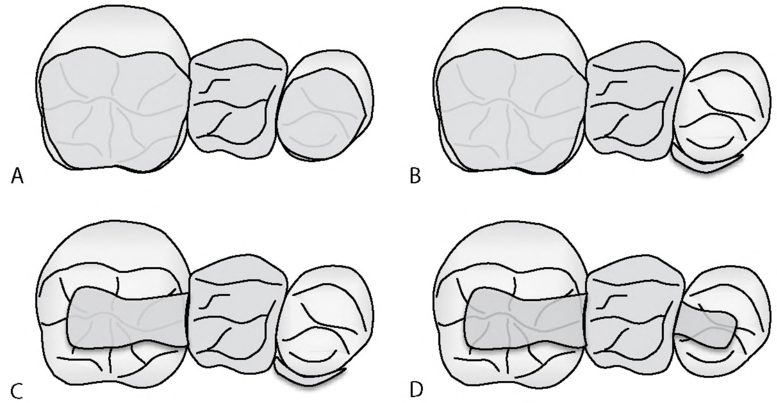

Table 2 Retainer characteristics of surface, inlay and hybrid retained FPD

Type of FPD	Mesial retainer	Distal retainer	n	Pontic type		Jaw	
Surface retained	Uplay	Uplay	15	Premolar 14	Molar 1	Mandibula 11	Maxilla 4
Surface retained	Wing	Uplay	16	Premolar 16	Molar 0	Mandibula 10	Maxilla 6
Hybrid retained	Wing	Inlay	20	Premolar 20	Molar 0	Mandibula 6	Maxilla 14
Inlay retained	Inlay	Inlay	45	Premolar 25	Molar 20	Mandibula 18	Maxilla 27

Restorations

Treatment was performed by 6 experienced dentists, with adequate skills in adhesive techniques, according to a clinical protocol. Clinical procedures were performed during two treatment sessions: (1) tooth preparation, impressions and provisional restorations; and (2) try-in, placement of the FPD, and finishing. Tooth preparation involved removal of existing restorations and creating cavities with slight divergence of cavity walls and rounded angles. Inlay-cavities required adequate volume and support for the FRC substructure, at minimum 2 x 2 x 2 mm in size. Surface retainers with a minimal thickness of 0.4 mm at the canines were provided with palatal slots and distal grooves depending on the preference of the operator. Uplay retainers were made without tooth preparation in case occlusal space was available. Impressions were made with a polyvinyl siloxane material. If present, cavities were protected with a provisional filling material for the period of the laboratory procedure.

FPDs were made in dental laboratories on full arch stone casts, which were isolated with separating agent. The fiber framework consisted of manual resin wetting requiring unidirectional preimpregnated glass fiber bundles (StickTM, Stick Tech Ltd, Finland). Each bundle consists of about 4000 glass fibers, with a diameter of 17 µm, embedded in a porous PMMA matrix. Glass fiber reinforcements were manually impregnated with BisGMA-TEGDMA based light polymerizing monomer resin (Stick Resin, Stick Tech Ltd, Finland) to form a PMMA-dimethacrylate semi-inter polymer network (IPN) [12, 13].

Before the fibers were placed on the cast, a thin layer of flowable composite was applied at the retainer area, which was not light-cured upon placement of the fiber bundle. After light polymerization, the framework was veneered with composite resin (in Turku and Umeå: Sinfony (3M ESPE, Germany); in Nijmegen: Artglass (Hereaus Kulzer, Germany)). The composite resin was built incrementally using a heat-light polymerization oven (in Turku and Umeå the 3M ESPE oven; in Nijmegen the Heraflash).

In the second treatment session, provisional restorations were removed and the abutment teeth were cleaned from debris. In most cases the fit of the FPD was checked using a silicon material (Fit Checker, GC, Japan); if needed the fit was adapted using diamond burs. Rubberdam was used in Nijmegen only, in about 50% of the cases. The bonding surface of the FPD was treated with the monomer resin. The resin was left unpolymerized, shielded from light, for at least 3 minutes to allow the resin to penetrate and activate the semiIPN-phase of the polymethylmethacrylate polymer matrix of the FRC framework. FPDs were luted with resin composite cement (Turku and Umeå: Compolute (3M ESPE, Germany) and Variolink (Ivoclar Vivadent, Liechtenstein); in Nijmegen: Twinlook (Hereaus Kulzer, Germany) and Panavia F (Kuraray, Japan)) according to the manufacturer's instructions. After removal of excess material, the resin composite cement was light cured for 20 seconds per surface. After polymerization, restoration margins were finished. Occlusion was adjusted with fine diamond-burs and the restoration was polished using rubbers and polishing discs. Patients received individual instructions to maintain plaque control.

Evaluation

For specific evaluation of the FRC FPDs, the majority of patients were invited for a check-up once a year, up to five years at minimum. Besides these check-ups, patients were advised to contact the dentist from the university clinic in case an event occurred concerning their FPD. The performance of the restorations was evaluated by clinical examination. Caries and periodontal status, wear of the restoration, discoloration, fractures and dislodgements were recorded. During the years 2005-2007 all patients with FPDs that were at least 4.5 years old and whose records did not already indicate a failure or removal of the restoration, were invited to participate in a clinical examination.

During the follow-up period, all interventions were recorded. Interventions may vary from finishing in case of chip fractures through repair by adding resin composite to renewal of the restoration. When records indicated interventions, the date and type of repair were recorded. If FPDs were repaired more than once, the first date of repair was used. The FPDs that could be rebonded after dislodgement were rebonded using the same procedure as had been used originally. Modes of failure were recorded as: 1) fracture of framework; 2) debonding one end; 3) dislodgement; 4) delamination of the veneering composite; 5) combination of problems. Fracture of the pontic, while the framework was still intact, was recorded as delamination.

Analysis

All restorations were included as individual cases. Two failure categorizations were used:
<u>Repaired needed</u>: Includes interventions, such as polishing and finishing after chipping of small fragments of the veneering resin composite, repair of small delaminations with restorative resin composite, or adding fibers at the connector area of the fiber framework, during follow-up. Also rebonding of FPD after dislodgement or debonding of one retainer was considered a repair.
<u>Failure occurred</u>: An FPD was considered failed, when problems, such as fracture of the restoration, unreparable delamination of the veneering resin composite, and combination of problems, that could not be repaired with the FPD in situ, occurred during follow-up.

Survival was analyzed at different levels: on the level of 'success' and on the level of 'survival' using the two criteria of failure as endpoints. In both cases, restorations not meeting the criterion of failure at the end of the observation period were labeled "censored". Reasons for drop-out were traced.
Kaplan Meier survival analyses were done for the complete group of FPDs and discriminated according to retainer type and preparation form. The 95% confidence intervals for survival probability at 5 yrs were calculated. Correlations between variables were crosschecked and possibilities for Cox regression analyses were omitted because there are two many variables. The analyses were performed with SPSS version 16.0 (SPSS Inc., Chigaco, IL, USA).

Results

Mean follow-up time was 5.5 years, with a minimum of 4.5 years and 8.9 years as the maximum. During the follow-up period 11 patients with 12 FPDs were lost to follow-up (12.5%). These drop-out patients could not be contacted or were not able to participate in follow-up examination mostly because of travel distance. The lifecycle of the FRC FPDs included in this study is shown in Figure 2. Twenty-eight FPDs failed because of fracture, delamination or debonding. The operators regarded 20 of them as reparable. Failures occurred at a mean follow-up of 18-24 months (reparable and non-reparable failures respectively). The rebonded or repaired FPDs failed again in 5 cases within 2 to 40 months.

The percentage distribution of failure modes is shown in Figure 3. For reparable failures, delamination and debonding of one retainer-end were the main problems (52% and 28% respectively). Fracture of the framework and delamination were the main causes for failure (38% and 20% respectively). One FPD was replaced because of caries in the abutment tooth. Combined problems included a case showing delamination and fracture of the pontic area (failure) and in three other cases a combination of debonding and fracture of the retainer (one failure, two repaired). Only FPDs with surface retainers showed debonding.

Survival curves for 'success' and 'survival' up to 5 years are shown in Figure 4. Kaplan Meier survival rate at 5 years was 71.2% (SE 4.8%) for success and 77.5% (SE 4.4%) for survival. Although survival rates for 'survival' at 5 years seemed to be higher for inlay retained FPDs in comparison with surface and hybrid FPDs (82% vs 78% and 66%),

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Figure 2 Lifecycle of posterior FRC FPDs during the follow-up periode (4.5 – 8.9 yrs)

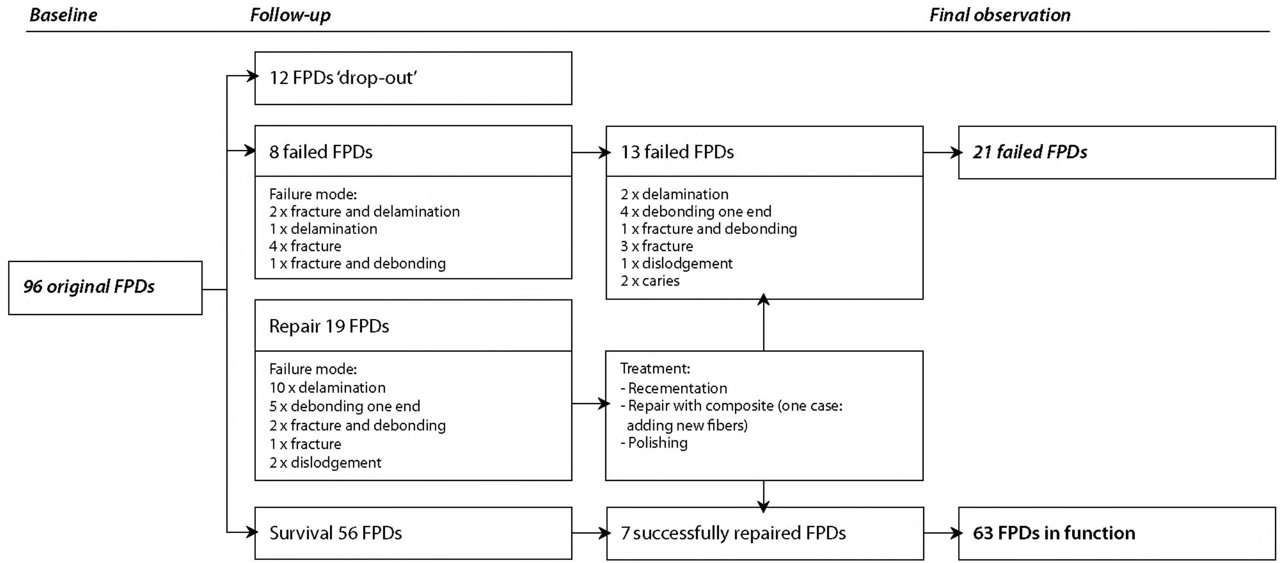
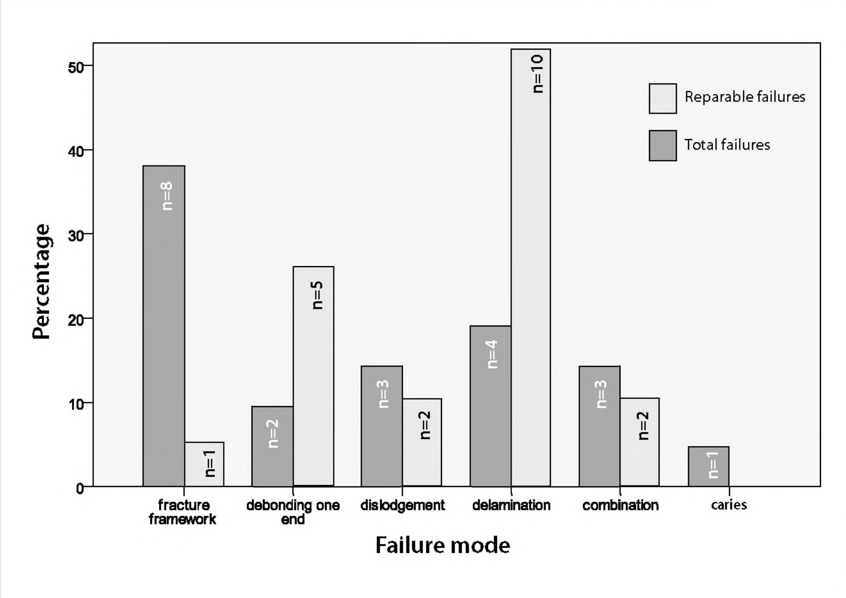


Figure 3 Failure mode in categories at repair and at total failure



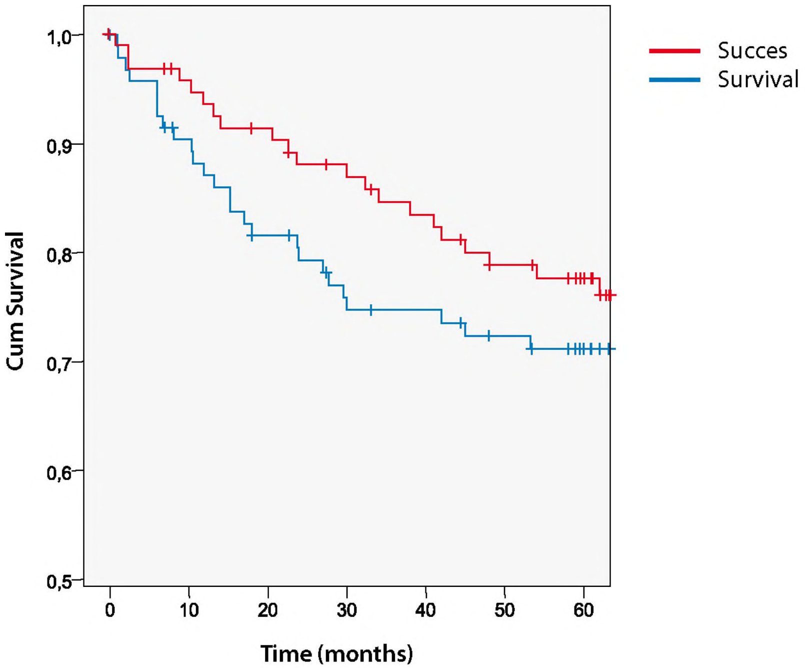
survival rates for different groups (surface vs hybrid vs inlay) were not significantly different for both 'success' and 'survival' (Fig. 5; log rank test $p > 0.05$).

The two veneering materials were exclusively related to the different institutes. Therefore, analyses on the survival rates for institutes or material were not feasible. In addition, interaction between independent variables such as operator, patient age, preparation, type of FPD and luting cement hampers a valid regression analysis.

Discussion

This study reports clinical follow-up data on three-unit posterior indirect FRC FPDs after a mean service time of 5.5 years. This study forms part of a trial including the previously referred anterior FPDs. A survival rate of 78% was observed for posterior FPDs, which is higher than the 63% survival rate we found for anterior FRC FPDs after 5 years [11]. Thus, our hypothesis is rejected. Other published clinical studies on FRC

Figure 4 Restoration survival probability as a function of time for posterior FRC FPDs (n=96)



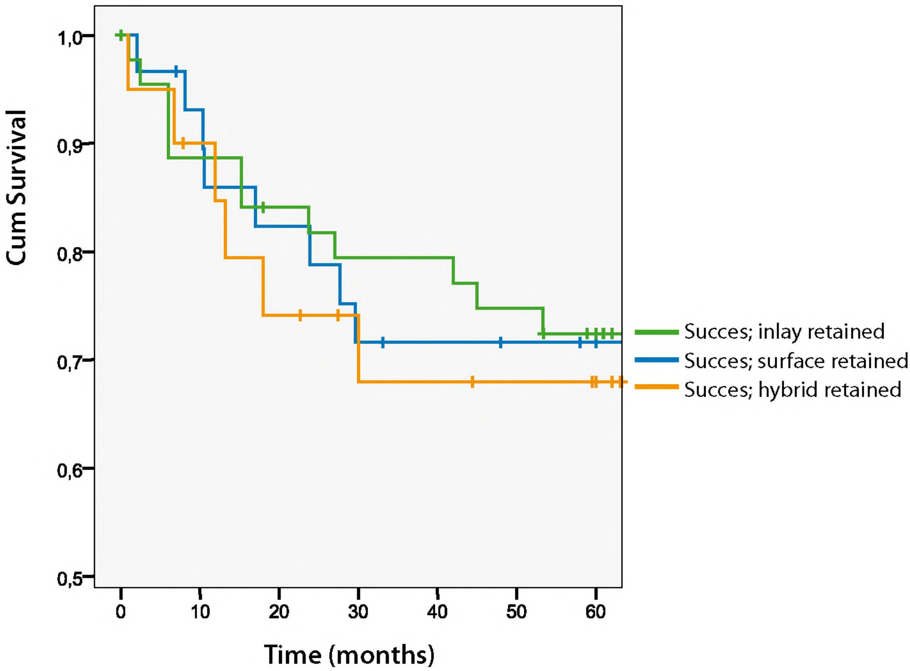
FPDs do not discriminate between anterior or posterior bridges and survival rates of 75-95%, after shorter follow-up times of 3-4 years, have been reported. A study using similar (manual resin impregnation requiring) FRC material, but mixed FPD designs, demonstrated a survival rate of 93% after 3.5 years [14]. Given the longer follow-up time of our study, the present result seems to be in line with the abovementioned survival rates.

The trial as a whole was a mix of a prospective trial and a retrospective evaluation. The strict protocol of a randomized clinical trial could not be maintained, but generally accepted limitations of retrospective studies, like their non-protocolized design, are not applicable to this study. Operators worked according to a clinical protocol and the restoration design was restricted to three-unit FPDs. However, it was not possible to assign patients and type of retainers on a random basis and also the three clinical centers differed on details concerning clinical and technical procedures. These differences complicated analyses and prevented firm conclusions on items of interest. On the other hand it gave us the opportunity to obtain indications of the clinical performance of FRC FPDs with small differences in design. During analyses it appeared that survival results of one operator in this study substantially differed from the others. The slope of the survival curve of the FPDs made by this operator differed, and this could not be explained by design, material, or dentist factors. Possibly, differences in case selection could be the reason. If this operator is excluded from the analysis the survival rate would increase to 84%.

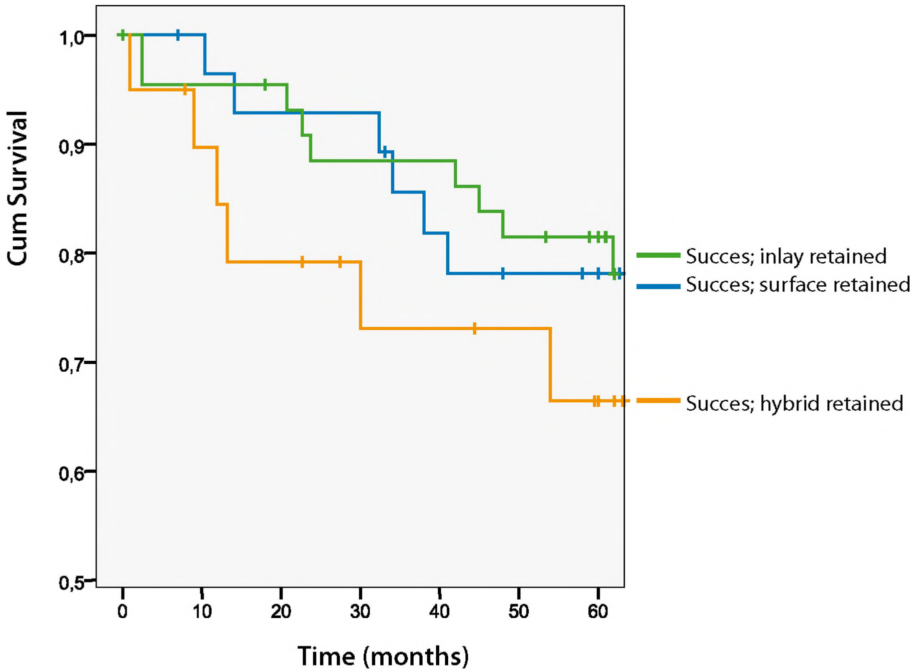
Striking is the difference in survival of three-unit FRC FPDs in the anterior compared to the posterior area. To our knowledge, no other study on FRC bridge constructions has been published that could confirm or refute such a difference. The difference between survival of anterior and posterior FRC FPDs can be traced to a difference in volume of the constructions. The retainers of anterior FPDs are thin and micro-cracks in the veneering composite layer can easily occur, followed by further degradation of the veneer. The volume of composite on top of the fiber frame of posterior bridges is generally much higher and the bulk of material prevents early crack forming. Indeed, we found relatively more delaminations with anterior than with posterior FPDs. Furthermore, it had been stated that the weakest part of a bridge construction is the connector area [15, 16]. For anterior FPDs the connector area is relatively thin compared to the connector area in a posterior FPD. Moreover, loading of posterior bridges is expected to be of vertical angulation with lower change of rotation forces compared to anterior bridges. Given the volume difference, the anterior bridge has lower opportunity to withstand these occlusal loading forces.

When studying metallic resin bonded FPDs with retainers of the Maryland design with minimal, strategic preparations, it was found that anterior FPDs survived better than posterior FPDs [17, 18]. Considering the high survival rate in the anterior region compared to posterior, Creugers did not recommend to prepare abutment teeth extensively. In the present study, the difference in preparation of abutment teeth between anterior and posterior is expected to influence the survival as main difference in design. It can be assumed that preparation for anterior FRC FPDs thus is recommended.

Figure 5 Restoration survival probability as a function of time for surface FPDs (n=31), inlay FPDs (n=45) and hybrid FPDs (n=20)



A trend towards better survival of inlay-retained FPDs over other FPD designs was observed. Similar observations can be found in the literature [14]. An inlay retainer of sufficient volume (2 x 2 x 2 mm) seems to provide sufficient resistance against rotational forces when it can be adhesively retained to tooth tissues. Although surface retention may offer even more resistance against rotational and oblique detaching forces on the condition that the retainer is provided with axial support for example an occlusal rest, the volume problem as outlined in the previous paragraph may here also be of importance to the formation of cracks, and finally failure of the bridge.



Two different veneering composites were used while manufacturing the FPDs, namely Artglass and Sinfony. Conclusions towards the behavior of materials could not be drawn from the results in this study, because of the strong correlation between materials, institutes and FPD design. Compared to laboratory composites it is described that Artglass has lower mechanical properties in terms of fracture, tensile, compressive, and flexural strength [19]. However, the material properties of both composites do not deviate to a great extent and their behavior should be quite comparable.

Veneering composite fractures i.e. delaminations constituted the mode of failure most commonly observed. This is most likely a result of insufficient support for the pontic area offered by the solely unidirectional framework fibers as applied in our study. Clinical reports demonstrated an improved resistance against veneering composite fractures of a larger substructure volume at the pontic area by using a wrap around design (Freilich et al., 2002; Monaco et al. 2003), or a bundle of fibers oriented perpendicularly towards longitudinal fibers [10, 20, 21]. We furthermore found fractures of the fiber framework. Like the anterior FRC FDPS of this trial, the low fiber volume fraction of a manually impregnated composite may result in insufficient strength of the material. Therefore, advice is to apply more than one fiber bundle in the framework, additional reinforcement at the pontic area, and to provide sufficient volume of composite at the retainer and connector sites.

All in all it can be stated that, considering the tissue saving characteristics, relatively low costs and tooth colored material, these kind of restorations are an interesting (semi) permanent solution. The results in this study suggests that the application of FRC FPDs in the posterior region can be a good alternative, especially in cases of young patients where implant therapy is not (yet) indicated.

Conclusions

In the present study, three unit posterior FRC FDPs demonstrated a success rate of 71% during an observation period of 4.5 to 8.9 years. If repaired FPDs were included as successful performing constructions, the survival rate was 78%. Survival rates of inlay, hybrid and surface retained FPDs did not significantly differ. Delamination, debonding and fracture of the framework were most prevalent failure modes and debonding was seen only for surface retained FPDs.

Acknowledgements

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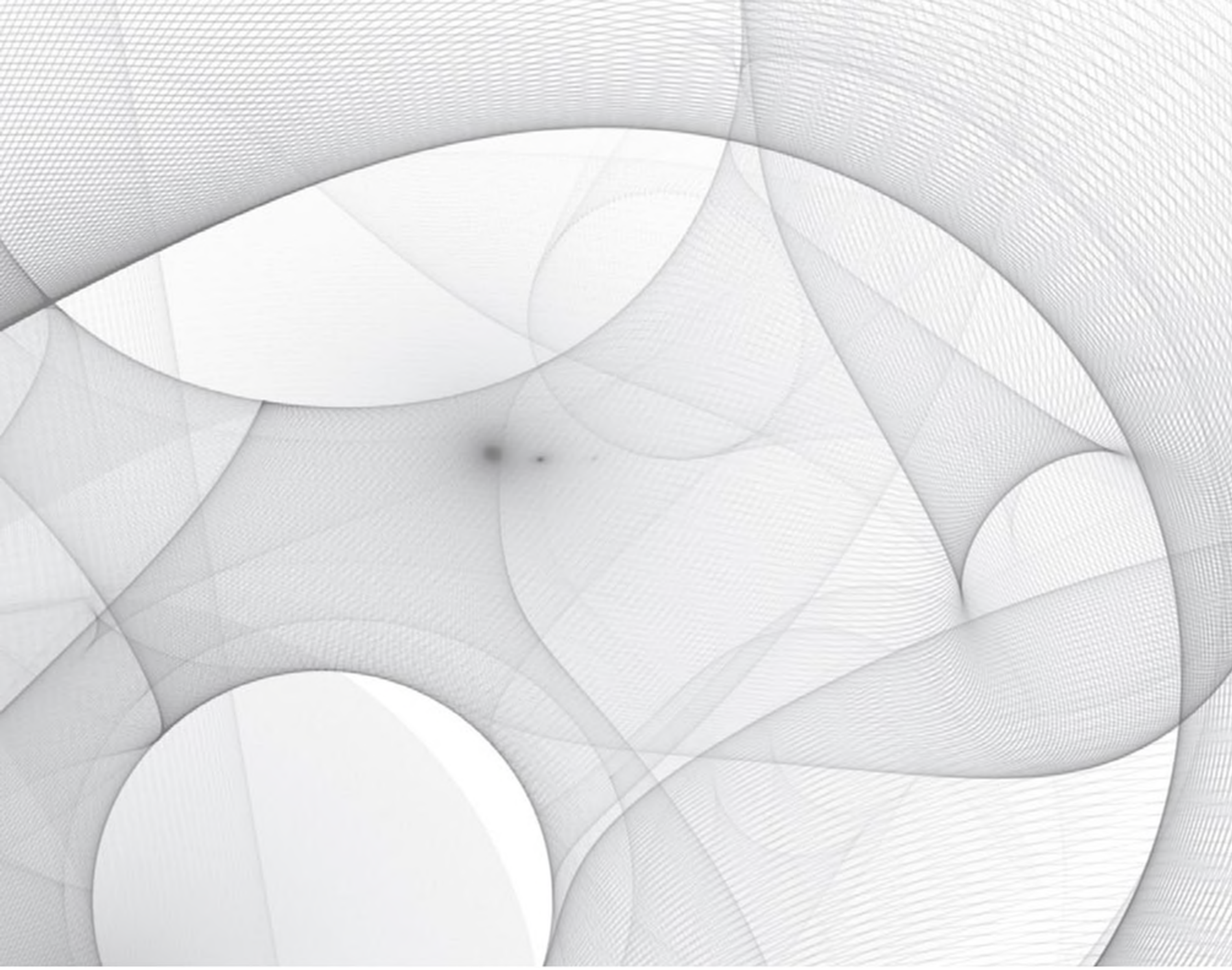

Chapter 6

Laboratory simulation of a clinically failed fiber-reinforced fixed partial denture in the anterior area

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Celeste C.M. van Heumen, Joop Wolke, Nico H.J. Creugers, Cees M. Kreulen.
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Dental Materials; submitted.

Abstract

The standard method for laboratory testing of fiber-reinforced materials is the three-point bending test. The purpose of this study was to develop a test design that supports new developments in FRC framework design on the basis of fractography principles. Therefore, the loading conditions of a typical failure mode of an FRC FPD as most commonly seen in the anterior area were simulated. Case simulation of a three-unit FRC FPD with a Maryland design with two surface retainers was performed in a universal testing machine. Testing was performed in 3 series. Series A: static loading of the FPD at the occlusal contact points (retainers and pontic) and in the same direction as in the clinical situation. Series B: static loading at the pontic only, to simulate overloading. Series C: dynamic loading of the FPD as in series A. Examination of the fractured restorations was performed by visual examination using SEM. Fractures, delamination and crack formation, specifically in the retainer area, as seen in the clinical situation were observed in the laboratory situation as well. The present results suggests that this new laboratory method can be valid for further development studies into the design of FRC FPDs in the anterior area.

Introduction

Fiber-reinforced composite (FRC) materials for applications in fixed partial dentures (FPDs) gained popularity in clinical dentistry over the last years. Nevertheless, long-term results for FRC FPDs are only limited available from retrospective clinical evaluations and case reports. A systematic review on longevity of resin-bonded FRC FPDs using those data obtained a calculated survival rate of 72% after 2-5 years [1]. The rationale to apply FRC materials to bridge constructions stems from results of laboratory research, especially from 3-point bending tests under controlled conditions [2]. Positive characteristics in terms of fracture strength, failure mechanism and internal stresses have been reported.

These load-to-fracture tests represent the ultimate loading experience of bridge constructions which most possibly occurs in the posterior area. If the material performs well, then other purposes in lower loading conditions, as possibly in anterior FPDs, are expected to behave at least equivalent. Surprisingly, recent data suggest that anterior surface retained FRC FPDs show lower survival after 5 years instead of the expected higher life-span compared to inlay- and surface retained posterior FRC FPDs (64% survival versus 78%) [3]. This now indicates that laboratory results of posterior constructions cannot be translated directly to constructions in the anterior region. A restricted life-cycle of anterior FPDs has not been reported yet.

Another unresolved issue so far is the difference in observed type of failures of FRC bridge constructions in laboratory settings compared to clinical failures. In-vitro analyses on occlusally loaded FRC FPDs show high tensile stress in the connector areas between pontic and abutment retainer [4, 5]. Unfortunately this possible cause of fracture does not correspond to reported clinical failure. The most frequently reported mode of failure of posterior FRC FPDs is wear of the veneering composite resulting in delamination and exposure of the fiber framework [6-10]. Less often fracture of the framework has been reported [11-13]. Moreover, the few laboratory studies on anterior surface retained FPDs are inconclusive regarding the expected mode of failure [14, 15]. In a clinical study from our group on anterior FRC FPDs, predominantly framework fractures in the connector areas and surface retainers were found, preceded by some delamination [3].

Briefly, the failure behavior of anterior FRC FPDs is disappointing and design parameters of these types of constructions should be improved using simulation studies. As described above, however, the predictive value of existing load tests is limited. The aim of this study is to develop a simple and valid simulation of the loading of an anterior FRC FDP that can be used to develop new FRC (framework) designs We made a laboratory loading test to reproduce the failure behavior that was typical of anterior FRC FPDs, represented by a clinical model case with a known history [2] . After loading the simulation set-up, the results were compared to the clinical outcome of the case and in an iterative process the test set-up was adapted.

Materials and methods

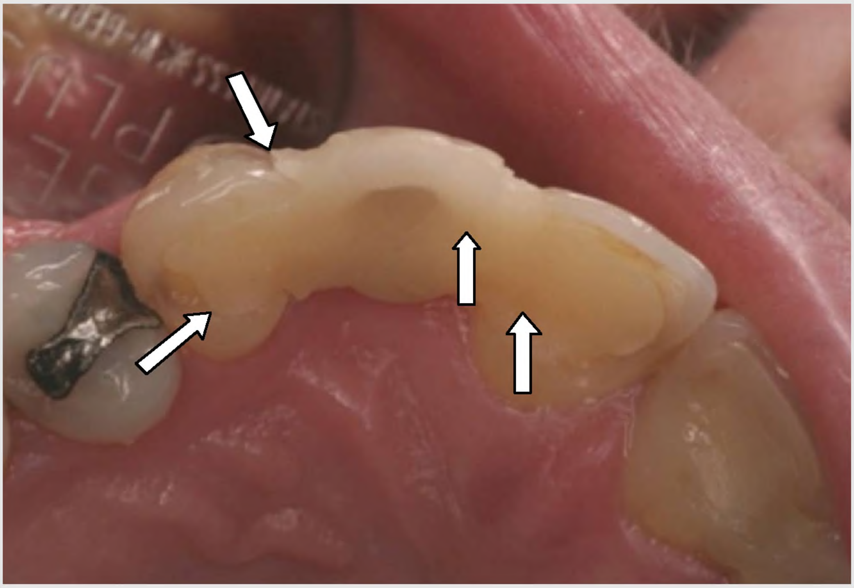
The model case

The clinical case that was reproduced to model failure behavior was a typical anterior FRC FPD made as replacement of the lateral right incisor in a 52-year old woman. The life-span of the FRC FPD was 4.5 years. The FPD was of a Maryland design with two surface retainers. The FPD was made by a dental technician using one standard unidirectional preimpregnated glass fiber bundle (Stick TM, Stick Tech, Finland) as the framework material and ArtGlass (Hereaus Kulzer, Germany) as the veneering composite. During the life-cycle the construction was monitored at yearly intervals and after 1 year wear was seen at the palatal retainers. At failure, the mode was chipping by delamination at the abutment retainers and fracture of the framework in the connector area (Figure 1). The fractured FPD could not be re-assembled, since parts of the retainers were attached to the abutment teeth. However, the plaster working casts for the fabrication of the FPD at baseline had been stored and the original form of the construction was laid down.

Fabrication of the samples

The baseline working cast of the model case was duplicated 15 times in epoxy resin (Araldite D, Ciba Geigy, Germany), while leaving two empty sockets adjacent to the toothless space of the lateral right incisor. A upper right canine and a upper right central incisor were selected from standard anatomically polymer teeth (KaVo, Germany) and were ground to match the original surface preparations of the abutment teeth. These abutment teeth were duplicated 15 times in monomer resin (Vertex 2 SMS Ivory, The Netherlands) and were embedded into the sockets in the epoxy models using monomer resin.

Figure 1 The model case: anterior FRC FPD that showed typical clinical failure characteristics: wear, chippings by delamination at the abutment retainers and a fracture line in the connector areas (indicated by arrows in the figure)



For each of the 15 dental models a three-unit anterior FRC FPDs was made by the same dental technician as the original FPD. The framework material was identical to the original FPD, the veneering composite resin was Clearfil APX (Kuraray, Japan). Materials were utilized according to the manufacturers instructions. The fiber framework consisted of one standard commercially available bundle and was applied to the teeth after application of flowable composite (Stick Flow, Stick Tech, Finland) and ran from the mesial preparation outline of the central incisor with a moderate U-curve in the toothless space to the distal preparation outline of the canine. After light polymerization, the framework was veneered with composite resin at the retainers and the pontic was built incrementally. To ensure accurate reproduction of the dimensions of the constructions silicone molds were used that were derived from the original model case FPD.

For the placement of the constructions the bonding surface of the FPDs was treated with monomer resin. The resin was left unpolymerized, shielded from light, for at least 3 minutes to allow the resin to penetrate the polymer matrix of the FRC framework. The receiving surface of the retainers was cleaned with alcohol and the FPDs were luted with resin composite cement (Panavia, Kuraray, Japan) according to the manufacturers instructions. After polymerization, restoration margins were finished.

Test set-up and loading

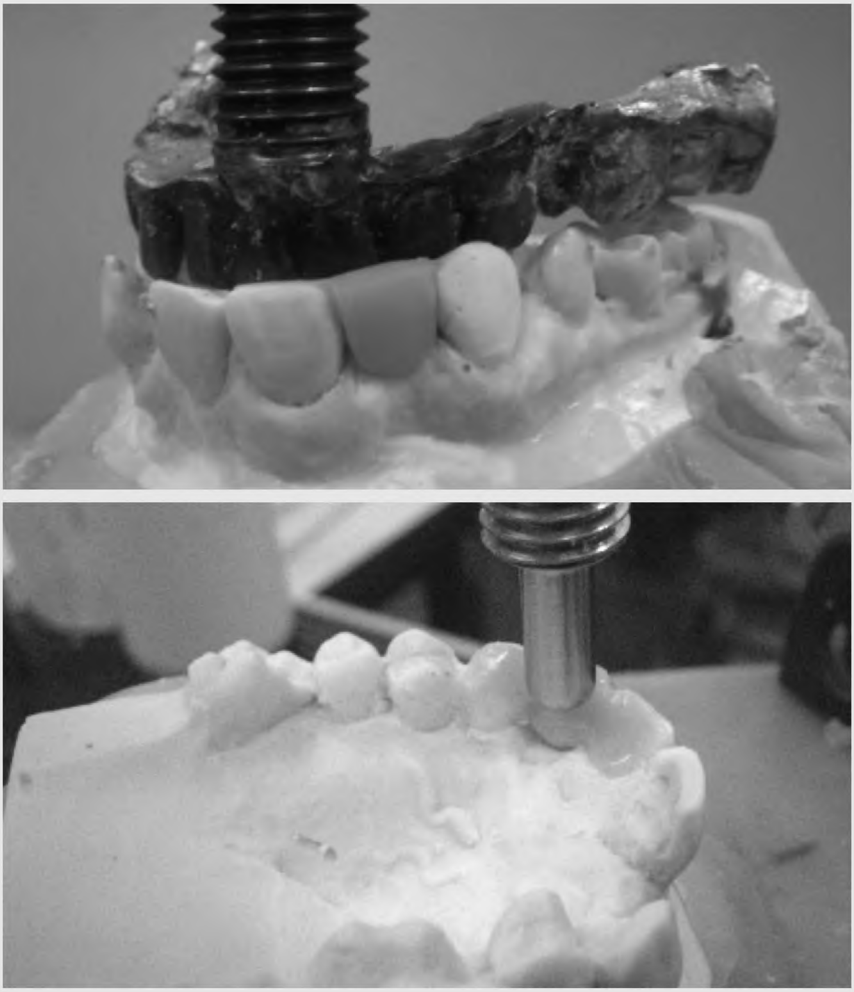
Each specimen was subjected to vertical loading in a universal testing machine (825 Mini Biomix II, MTS, Eden Prairie, MN, USA), with a crosshead speed of 0,5 mm/min. Loading was stopped at the first sign of failure, as indicated by the sudden load drop of the digital monitoring by the loading machine. The testing was performed in 3 series as to underline each step of the development of simulation: (A) static loading of the FPD with the same occlusal contacts (retainers and pontic) as in the clinical situation, (B) static loading at the pontic only to simulate overloading, and (C) dynamic loading of the FPD as in (A).

In the first series (series A; n=5), a replica of the lower anterior teeth of the subject was used as the loading object. The replica was made of a cobalt-chromium alloy and soldered to a screw that fitted the testing machine. The metal replica and the epoxy model were mounted in the testing machine in a way the clinical occlusion was reproduced. Distally from the FPD the occlusal contacts were removed from the model, except from the second molars. By this procedure a four point contact was created to ensure loading of the FPD only, and to prevent kipping (Figure 1).

In order to subject the construction to a maximum tensile load, each specimen in series B (n=5) was loaded by a round-end stilus to simulate a single occlusal contact at the pontic of the FPD. The load was identically placed at the palatal side close to the incisal edge. The direction of loading was identical to series A.

In series C (n=5) dynamic loading was performed using the metal replica of the lower teeth and the staircase method was applied. The specimen were loaded at 5 Hz inducing a sinusoidal stress until failure or to a maximum of 25,000 cycles [16]. For the first specimen, the test started at approximately 50% of the flexural strength, as it appeared from the static load test in series A. When specimen survived, stress was increased with 100N subsequently, until failure.

Figure 1 Test set-up using an individual stilus (left; series A and C) and a stilus with rounded tip (right; series B)



Examination of fractured restorations

After fracture two independent and calibrated observers inspected the fracture sites of the samples. Failure patterns were visually examined with both light microscopy and scanning electron microscopy (SEM) (Jeol, type 6310, Tokyo, Japan). Location of the fracture origin was first estimated at low magnifications, 50x to 150x, using different surface landmarks as surface damage, structural defects and crack branching. At high magnifications, up to 2500x, fracture orientation was visualized and cracks were identified. Differentiation was made between adhesive fractures, framework fractures, and resin composite fractures.

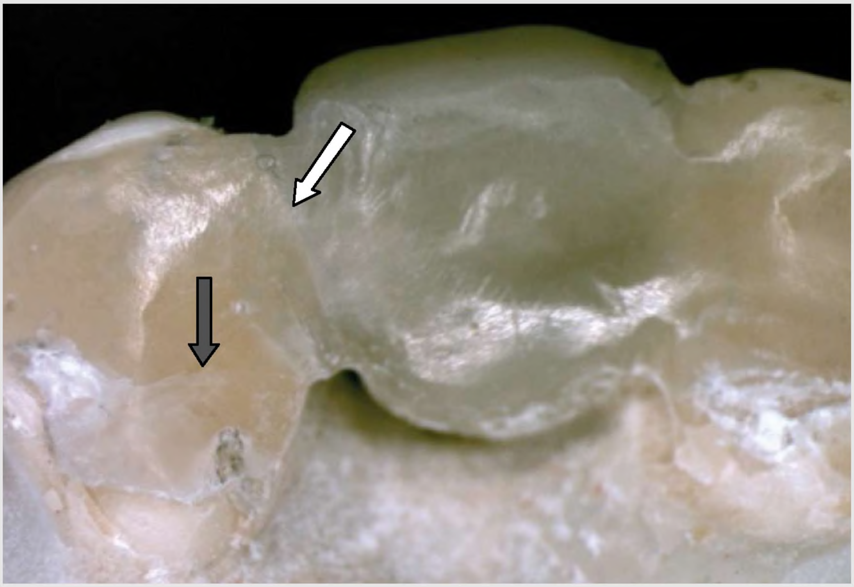
Results

Clinical behavior of the model case FRC FPD was characterized by a gradual wear of composite, followed by delamination and fracture of the FPD. Specimen from both series A and series C showed representative behavior including crack formation, delamination and fracture; fracture behavior of specimen from series B deviated. Obviously, only in series C gradual wear was observed.

In detail, all specimen of series A showed multiple cracks at both abutment retainers, originating from the inter occlusal loading points (Fig. 2). Crack formation seems to be limited to the veneering resin composite resulting in delamination of the veneer with chipping of the cervical part of the retainer (3 specimens). In 2 specimens clear exposure of fibers was seen (Fig. 3). In the connector area framework fracture was seen predominantly between the canine and the pontic. Fracture lines and cracks that originated from the retainer propagated along the fibers to the tensile surface of the connector and then extended vertical in the low volume connector composite.
The different failure mode of series B was illustrated by pontic fractures that originated at the loading point and extended along the incisal edge through the pontic to the buccal side as shown in figure 4. Fractures propagated up to the composite-FRC interface, which can be interpreted as adhesive fractures. Fractures did not seem to propagate through the fiber frame of the connector.

Mean strength of series A (static loading) was 1499 ± 174 N and dynamic staircase testing (series C) started at less than 50%, at 600N. Besides, mean strength value of series B was 791 ± 55 N. All specimens in series C failed after loading for a maximum of 25.000 cycles at 800N and they showed wear of the resin composite at the inter occlusal contacts. All specimen showed crack formation originating from the loading points at the retainers. These fractures extended to the connector area in 3 specimens. Two specimens showed cohesive fractures of the veneering composite (delamination), one at a connector and one at the cervical part of the pontic.

Figure 2 Light microscopic image (8x) of the fracture pattern of one of the samples in series A. Fractures of the abutment retainer, indicated by the black arrow, originate from the loading point. Another typical fracture line was located at the connector area (white arrow)



Discussion

Since behavior of anterior FRC FPDs cannot adequately be predicted by standard load-to-fracture tests [3, 12, 17], it is imperative to obtain a valid testing model to develop new designs of anterior FPDs. It therefore seems a logical step to simulate a clinical failure *in-vitro*. To our knowledge the described sequence to come to a relevant laboratory simulation of clinical failure of an FRC FPD has not been described yet.

Up to now, the three point bending test, whether performed as beam testing or using anatomical models, was the standard in FRC FPD research [18]. The predominant type of failure derived from these *in vitro* studies is mid-frame fracture as a result of delamination of the veneering resin composite of the pontic, not fracture of the connectors. The buccal or lingual surface completely separated from the fiber bundle

Figure 3 Series A: SEM image of the distal abutment retainer (image above), showing multiple fractures originating from the loading point. The image below shows the surface of the retainer with fractures and chipping of the veneering composite exposing the glass fibers at the cervical part of the retainer

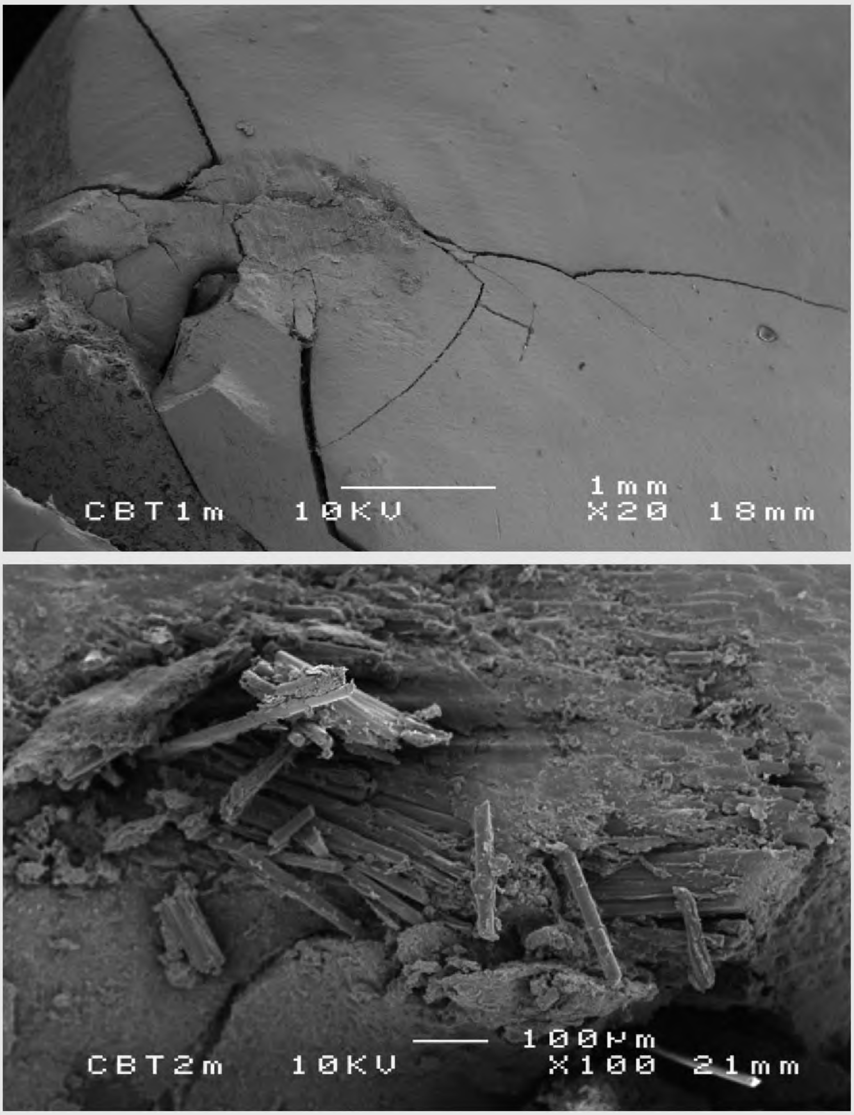
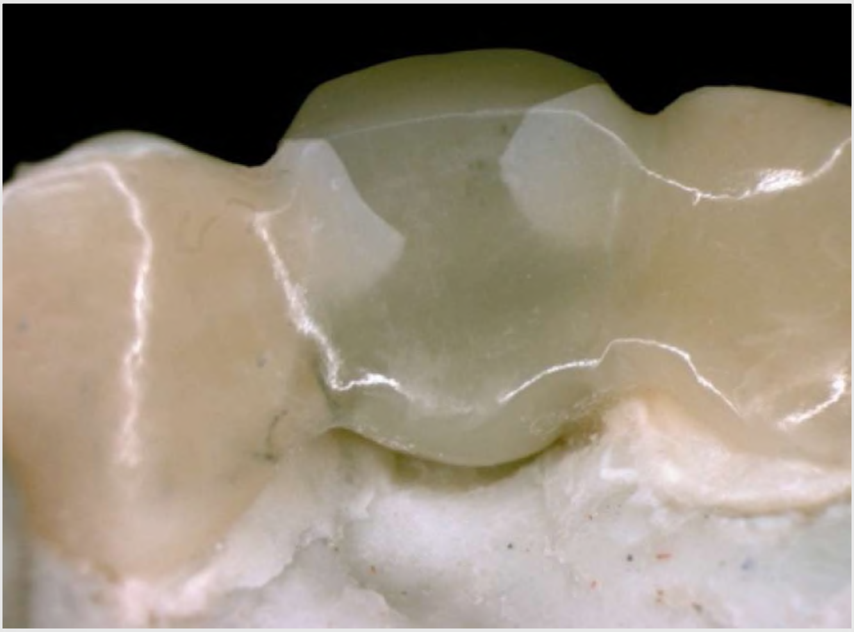


Figure 4 Series B: light microscopic image (8x) showing fracture lines that did not seem to propagate through the connector into the fiber frame



with a crack path in mesiodistal direction [19-21]. Two clinical studies confirmed this type of failure, but this typical type of failure seemed to be connected to two specific brands of fibers. This delamination problem has been shown to be diminished by using so-called high volume fraction FRC framework [10].

For reasons of availability, the specimen in the simulation were made with the resin composite Clearfill APX, instead of Artglass as used in the clinical model case. A different veneering composite might have influenced the behavior of the construction under loading. It has been described that Artglass has limited mechanical properties in terms of fracture, tensile, compressive, and flexural strength [22]. However, the material properties of both composites do not deviate to a great extent and their behavior was expected to be quite comparable. It can therefore be assumed that our loading test can still be used to reproduce the model case.

The FRC FPDs in the simulation and in the clinical model case were fabricated with one fiber bundle, without supplementary fibers. Freilich et al indicated that this way of construction must be susceptible to delamination of (a part of) the pontic [9]. Delamination is described as chippings with or without exposure of the fiber layer. Delamination of the pontic fundamentally differs from the failure mode as we have seen in the present simulation. In our clinical study on anterior FPDs that were made with a low volume fraction FRC framework we also found that delamination predominantly occurred at the retainer sites and not at the pontic [3]. Although the difference in clinical failure between anterior and posterior FRC FPDs is not understood yet, it may be related to differences of material volume to distribute stress as a consequence of occlusal loading. Also rotation as a result of active occlusion in the anterior region may play a role.
In this study we focused on simulation of the failure mode, not to simulate the exact clinical behavior of the construction. Therefore a periodontal ligament was not simulated. On the other hand, from the inadequate predictions of beam testing models, we aimed to use anatomical structures in clinical relevant loading conditions. Dentals casts were made of epoxy resin, which is a practical material with high fracture toughness. However, adhesion of resin composite cement to epoxy is poor. Since debonding was hardly observed in clinical studies [1, 17, 23], the solution was found to use methylmethacrylate abutments. This type of resin was found to have good retentive capacity for resin composite [24-26]. Indeed, debonding of the specimen did not occur.

Specimens in series A showed clear fractures or crack formation leading to the connector area. It was noticed that the cracks followed the fiber direction horizontally towards the connector and then deflected to the weakest part of the construction, the composite of the connector. This seems to confirm the suggestion that unidirectional fibers change the crack path and stress tends to be directed along the direction of the fiber framework and orientation of the fibers [14, 15]. Although set-up A resulted in quite a valid model, the preceding wear, which is clinically observed at the retainer surface, could not be simulated. Regarding this aspect, the dynamic testing as in set-up C improved the model.

As to meet three-point-bending models, set-up B was applied. From the literature, it appears that supported beams show mid-beam fractures in 3-point-bending tests while clamped beams have more diverse locations of fracture [27]. Series B was comparable to the clamped beam and fracture of the connectors was expected.

However, fracture originated at the loading point and SEM images showed that crack formation, unlike clinically observed, did not extend to the connector area. By set-up B the concentrated loading of the pontic by chewing a small, hard object might be simulated, but the low prevalence makes this set-up less valid.

We observed framework fracture, delamination of veneering composite, and crack formation. Framework fracture, often observed at the connector area, is generally preceded by a combination of smaller problems, concentrated at the thin resin composite veneer of the retainers [3]. After gradual wear of composite, chipping/ delamination, and crack formation fibers get exposed which facilitates moisture absorption. Occlusal loading then easily causes internal material failure. Moreover, delamination may reduce the overall stiffness as well as the residual strength, leading to structural cracks. Given the minimal difference in result between set-up A and C, however, simulation of wear by dynamic testing does not seem to be essential and neither humid conditions are expected to be of influence. Above all, results of set-up C showed more variation compared to those of set-up A.

We succeeded to develop a model that resulted in failure behavior that matched clinically observed failure of anterior FRC FPDs [3, 11, 12, 17, 28, 29]. The results strongly suggest that the static loading of anatomical models (series A) can validly be used for further development studies into the design of FRC FPDs in the anterior region. Using this model, alternative preparation and construction designs, directed to the retainer area, can be developed before implementation into clinical practice.

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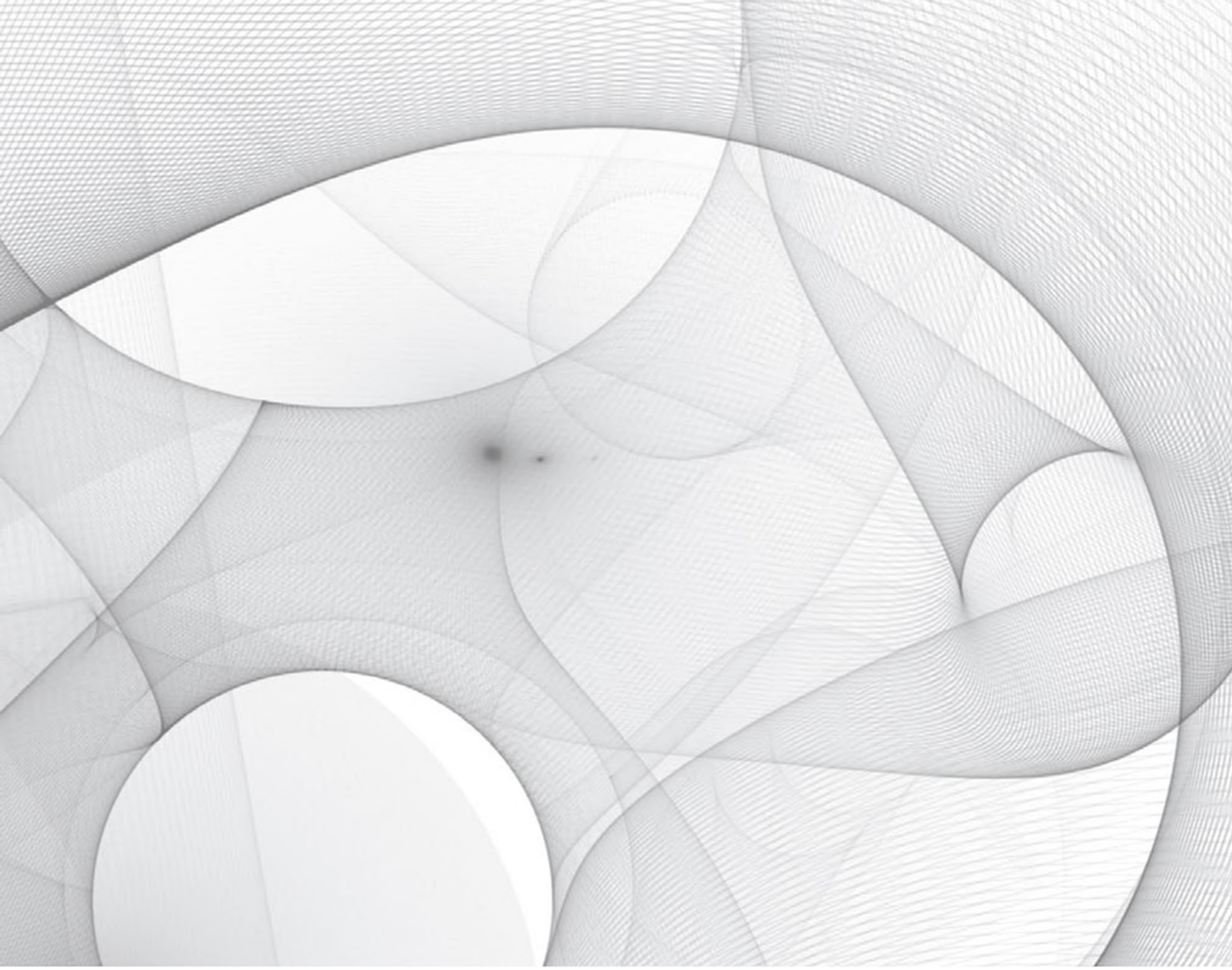

Chapter 7

General discussion

Abstract

This chapter discusses the findings of the different parts of this study in summary and the relations between the results. The main questions (as formulated in the General Introduction) are discussed related to the studies performed in this thesis. The limitations of different studies and their results are discussed. Recommendations for future research were formulated and finally conclusions were given

Fiber-reinforced composites are used in different dental applications, such as post and core systems and prosthodontic constructions. This thesis focused on the behavior of fiber-reinforced composite fixed partial dentures (FRC FPDs). The FRC FPD is considered potentially successful because of cost effectiveness and esthetic characteristics of the material. The FRC material offers the opportunity to create tooth replacing restorations with a tissue saving character, which is the main focus in minimal invasive dentistry. The traditional minimal invasive method to replace teeth is the metal resin-bonded FPD, in particular the Maryland FPD. The alternative FRC material has been introduced in dentistry in the early 1990s [1], and has developed markedly in these years.

Fiber-reinforced composite materials gained popularity because of their ability to adjust properties to specific needs. Laboratory findings point at a justified use of FRCs for specific applications. Generally, mechanical properties of FRC structures have been found to be superior to that of non-reinforced composites *in vitro*. A disadvantage of the material however, is the limited shear resistance, which is expressed in dental bridging constructions specifically. Besides, the incorporation of a fiber bundle requires a certain volume of the material. This can be problematic especially in the anterior area, where inter occlusal space in most situations is limited.

Several clinical studies have shown a substantial clinical performance of FRC FPDs with an overall survival rate of 75% after 5 years, which can be higher than FPDs with a metal framework [2, 3]. Despite the graving use of the material is, the clinical behavior is not fully understood yet.

In vitro studies on fiber-reinforced composite

The mechanical behavior of FRCs has been researched extensively. However, studies in this area have been conducted with many different materials and were performed with different aims [4-7]. To be used as a bridge material, material characteristics such as flexural strength and elasticity are of importance. Several studies have investigated these FRC properties in laboratory tests. Most *in vitro* tests are based on three point bending tests that specifically simulate the loading of an overlying bridge construction, such as an FPD [8-10]. The three-point bending test design is quite broadly used but an overall view of the reinforcing effect of FRC was lacking at the start of this study. The popularity of this type of test aids the comparison and pooling of results of separate studies [11].

A structured literature review is an excellent method to search for relevant studies and combine results of different studies on a specific topic. This technique is originally intended to analyze the literature on relevant clinical questions, but its objectivity supports the use in other types of research, like laboratory studies. To our knowledge, a structured literature review on laboratory data has never been conducted with beam testing as subject. Since standardization of laboratory tests is feasible to a high level, the comparison of laboratory results in a meta-analysis is very attractive.

As a result of combining data from 8 studies, it was shown in Chapter 2 that fiber incorporation reinforces resin composite beams, but an effective increase of strength or elastic modulus goes along with specific characteristics, such as the type of fibers and the fiber architecture. In general, it is suggested that placement of the fiber at the tensile side of the beam is the most efficient location for reinforcement [4, 5, 12, 13]. However, in this thesis it is shown that placement of fibers at the tensile side does not per se increase the strength more than placement at the compressive side, when unidirectional glass fibers are used (Chapter 2). Furthermore, in a regression analysis the influence of the fiber architecture was shown to be more important than that of the type of fiber. This means that for example the behavior of woven glass fibers is comparable to the behavior of woven polyethylene fibers, despite the different properties of the fiber material. Finally, in three-point bending tests as selected in Chapter 2, the load is applied only in one direction, which makes the reinforcing effect of an anisotropic material, such as unidirectional FRC, superior. Practically, occlusal forces will have various directions. In a clinical situation it seems therefore more desirable to use a material that behaves equally at loading from various directions. A bi- or multi directional isotropic FRC meets this requirement to a greater extent than an unidirectional anisotropic FRC. It therefore can be questioned if the results from three-point bending tests using unidirectional FRCs can be translated to clinical applications. Especially in the anterior area loading conditions differ from standard *in vitro* tests.

All in all, results from the meta-analysis suggests that in unreinforced resin composite beams the type of resin composite has an influence fracture strength and elasticity. As described by Gohring, microfilled composites are more prone to fracture in beam testing then hybrid composites [14-16]. If fibers are not located in the area of tensile stress, the incorporation of fibers does not lead to a significant increase of the elastic modulus of the composite material. As pointed out in the former, loading conditions in the anterior area deviate from the posterior and require different material properties. Therefore, it can be questioned if fiber incorporation is needed in all bridging applications. Besides, the application method in different types of FPDs is questionable. It has been described that flexural strength increases by fiber volume [15]. In clinical situations, in particular anterior applications, the possibility of increasing fiber volume is limited because of design limitations and esthetic reasons too.

In recent years FRC materials have been developed from manually to fully industrially resin impregnated glass FRCs. It is known that the manually impregnated FRCs (mainly applied in the laboratory tests as described in Chapter 2) will result in lower fiber fractions than the modern fully resin impregnated FRCs (30% vs. 65 wt%) and strength of the construction is related to the relative fiber quantity in the cross-section of the material [17-19]. Accordingly, static flexural strength of manually resin impregnated FRCs range from 250 to 350 MPa, while a range of 750-1200 MPa is reported for fully resin impregnated glass FRCs [12, 20]. Probably the incorporation of these further developed materials will lead to constructions with a high tensile strength. As a consequence, less framework fractures should be seen.

Clinical studies on fiber-reinforced fixed partial dentures

Results of clinical studies indicate that laboratory results are not completely valid for clinical introduction. For instance, the difference in behavior between posterior constructions and constructions in the anterior area was not expected on the basis of laboratory results. The ultimate test in the development of a material is the clinical application. Clinical results should provide insight into the applicability and restrictions of FRC FPDs. Clinical studies that have been published during recent show that there is still poor scientific evidence to advocate FRC FPDs as an alternative to conventional FPDs with crown retention [21]. However, there is a strong demand for minimal invasive alternatives and adhesive constructions, such as resin-bonded FPDs, are an interesting treatment option when tooth-replacement is required.

FRC FPDs can be used in different designs and with different aims and are mostly applied with retainer types other than full crowns. It is valuable to combine results from individual clinical studies and to draw conclusions on the survival of FRC FPDs. Therefore a meta-analysis on clinical data of FRC FPDs is described in Chapter 3. Survival rate as shown in this study was ≥ 72% after 2-5 years. Although it is difficult to compare this survival rata with the survival of other types of constructions, it is clear that the survival of conventional FPDs, with a reported survival of 89%-94% after 5-10 years, is higher [22]. Also survival rates of metal resin-bonded FPDs of 74%-88% after 4-5 years appear to be higher [22, 23].

Most clinical studies as described in the literature were based on limited groups of subjects. In Chapter 4 and 5 a retrospective study on anterior and posterior FRC FPDs with a relatively high number of subjects was performed. To our knowledge, hardly any long-term result on FRC FPDs has been published before. The 64% survival rate of anterior FRC constructions after 5 years found in the present study is a modest result for restorations that have a permanent character. Considering the 78% survival rate of posterior FPDs, there is a discrepancy in survival between restorations in the anterior and posterior region and it is not clear what the reason is. In the literature, several authors considered a posterior location to be a risk factor for FRC FPDs and it is generally expected that the most valid indication for resin-bonded FPDs is the anterior area. Results as described in Chapter 4 and 5 do not confirm this consideration, and in contrast, it can be stated that FPDs in the posterior region have a better prognosis. Results in this thesis emphasize that the application of FRC in anterior constructions until now, might be regarded to be for (semi)temporary solutions. Further development of the anterior framework design might lead to a higher survival probability.

A trend towards better survival of inlay-retained posterior FPDs over other FPD designs was observed. Similar observations can be found in the literature [2]. In Chapter 5 it is suggested that increased resin composite volume in the connector area contributes to a higher survival rate. This suggestion can be translated to the higher survival probability of posterior FPDs compared to anterior FPDs. The higher connector volume of posterior constructions compared to anterior constructions might be the reason of this observed difference.

Veneering composite fractures i.e. delaminations constituted the modes of failure commonly observed. These clinical failures, however cannot be directly compared to the observed failures of FRC bridge constructions in laboratory settings. In vitro analyses on occlusally loaded FRC FPDs show high tensile stress in the connector areas between pontic and abutment retainer [24, 25]. This suggests that fracture of the framework at the connector area is an often expected failure mode. In fact, in clinical settings, fracture of the framework in this part of the restoration has been reported less often [2, 26, 27]. In the anterior area the most predominant reason of failure was delamination of the surface retainers and crack formation that propagated into the connector area. Then framework fracture was present.

The need for material development

One of the advantages of the use of FRC in bridging dental restorations is the fact that the materials' use can be adjusted to the needs of the application. For example weak parts of the construction can be strengthened in the direction of loading by the addition of fibers with a particular architecture. Another advantage is the buffering capacity of fibers, which means that cracks can be conducted through the fiber bundle and in this way prevents fracture of the construction. Besides, even after fracture different parts of the restoration stay connected because of the present fiber bundle, decreasing the risk for the patient to swallow (a part of) the bridge.

The available space in the dentition and the design of the restoration framework determines the amount of resin composite that possibly can surround the framework. For example, a Maryland framework design in the anterior area consists of thin retainer types. The FRC is enfolded by veneering composite and the available inter occlusale space determines thickness of the retainers and thus the volume of veneering composite. The amount of resin composite, and thus the thickness of the retainer, probably influences the clinical success of the restoration (Chapter 4 and 5).

It was shown that metal resin-bonded FPDs with approximal grooves are more retentive than without grooves [28]. In this way more mechanical retention is applied, instead of relying on adhesive retention only. In Chapter 4 the difference in survival between anterior FPDs with and without additional mechanical retention has been described. Restricted to the surface retained FRC restorations, additional retention of the retainer hardly improved survival, but the failure mode of restorations with additional retention differed from purely adhesive retained FPDs. Thus, it remains unclear if additional mechanical retention is necessary. Adhesive strength of the composite-tooth interface should be sufficient to withstand shear forces. However, preparation or removal of tooth material contributes to the creation of an FPD with a higher volume of resin composite. It had been stated that the weakest part of a bridge construction is the connector area [24, 29]. Removal of tooth tissue at the connector area can contribute to a thicker connector, and thus contributes to a stronger construction. On the other hand, from our clinical study it appeared that in the anterior area the weakest part probably is the retainer site (Chapter 4). Most prominent was the fact that the retainers often were affected before the final failure of the FPD, which is incongruent with the few laboratory studies on anterior surface retained FPDs. Apparently, crack formation often leads to failure of the connector area, but originates in the retainer area. The laboratory study described in Chapter 6 confirmed this finding. SEM examination showed crack formation that originated in the retainer, but propogated to the connector area and deflected in this area along the connector. This suggests it can be necessary to prepare tooth material in the retainer area, to create a thicker retainer, which has better opportunity to withstand occlusal forces and wear. This aspect needs further research. However, preparation of (healthy) tooth material is not in line with the minimal invasive principle, which is the state of the art in dentistry at this moment [30]. FRC FPDs nowadays are mainly indicated for reasons of cost-effectiveness, in young patients, semi-permanent situations or the impossibility to indicate implant therapy. In these situations it is undesirable to sacrifice tooth material.

The need for a new method of laboratory testing of FRC FPDs

All in all, the design of in particular the anterior FRC FPD requires further research. Laboratory studies are a first step in the development of the design of anterior FPDs. It is advocated to redirect the study design for testing a bridge construction with clinically relevant applied forces and valid construction models (Chapter 2 and 6). Fracture behavior data from standard load-to-fracture tests do seem to simulate the clinical behavior of FRC FPDs in the posterior region. However, behavior of anterior FPDs cannot adequately be predicted by these tests [2, 31, 32]. Therefore, Chapter 7 describes a new method to simulate fracture behavior on the basis of a clinically observed failure of anterior FPDs. It is suggested that this model is useful to develop other FPD designs in order to optimize clinical performance. Although the exact clinical behavior cannot be simulated in a laboratory test, the failure behavior is an interesting reference to test FPD designs.

Conclusions

- o Under specific conditions it has been shown that fiber reinforcement has a beneficial effect on *in vitro* fracture resistance. However, the strengthening effect regarding flexural modulus is limited to the type of fibers. Besides, fiber architecture seems to be more important for the reinforcement of the resin material than the type of fiber.
- o From both literature studies and clinical retrospective studies it has been shown that the survival probability of FRC FPDs in the posterior area is higher than restorations in the anterior area. Main failure modes consisted of delamination of the veneering composite and fracture of the framework. However, delamination of the anterior FPDs mainly concerned the retainers, while in the posterior FPDs it was the pontic area.
- o There is no difference in clinical survival of different types of FPD (surface vs hybrid vs inlay retained FPDs) in the anterior as well as posterior area. Differences in survival percentages of surface FPDs with or without additional mechanical retention in the anterior area were not statistically different, although fracture behavior was different.
- o It is shown that the retainer and connector area for anterior FRC FPDs are predominantly affected at failure. This suggests further development of the framework design is required. For variations of the design of anterior FPDs a clinically relevant test set-up is needed. It has been shown to be possible to simulate a relevant clinically observed failure of an anterior surface retained FPD in a laboratory set-up.

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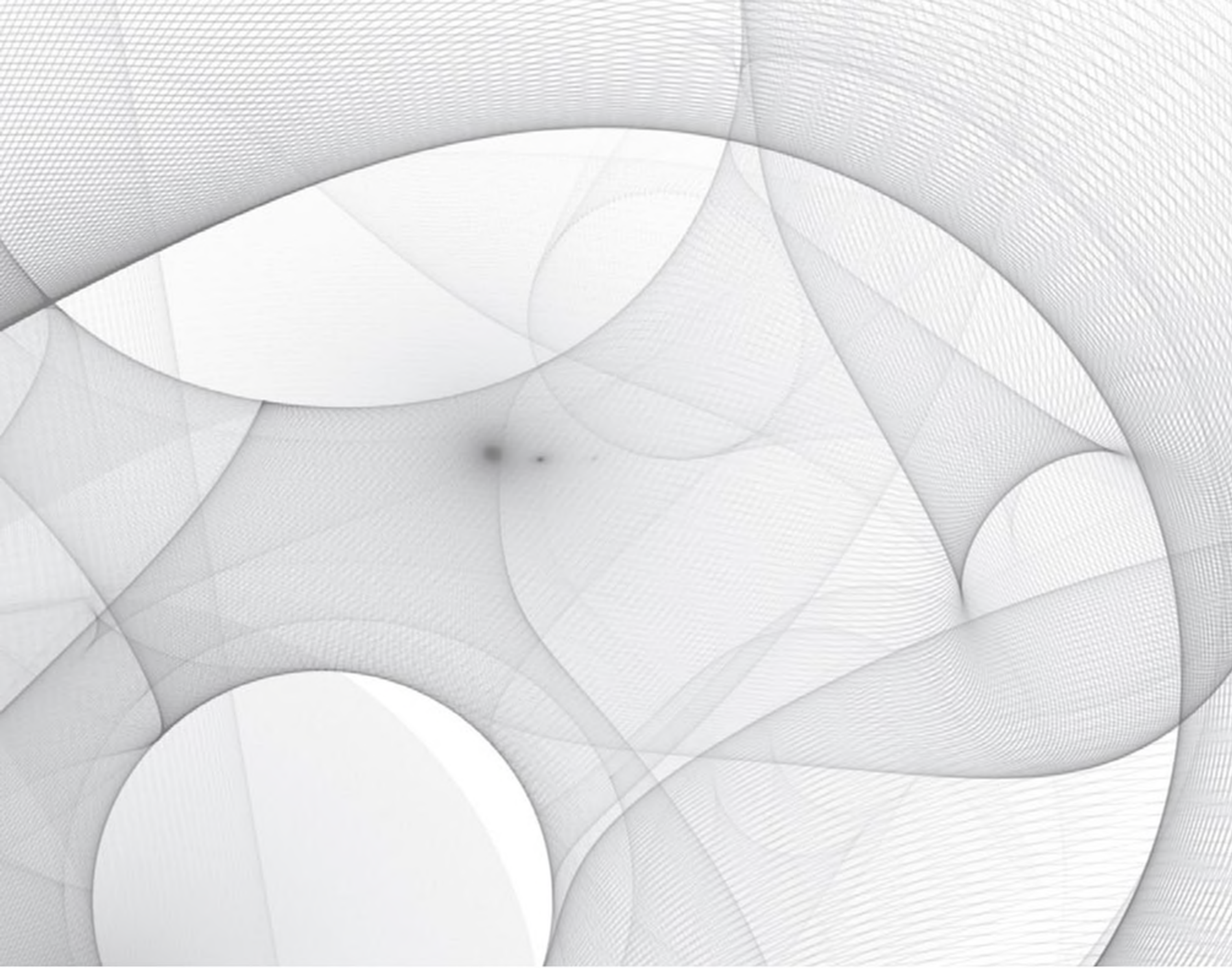


Chapter 8

Summary

This thesis was focused on the clinical and laboratory performance of fiber-reinforced adhesive fixed partial dentures, specifically in the anterior area. At this moment there is no unambiguous guideline for optimal design of the framework of anterior FRC FPDs, which is one of the drawbacks for the dental practioner to use FRC material. Considering the minimal invasive dentistry, the application of adhesive FRC FPDs can be an interesting alternative to metal resin-bonded and conventional bridges.

Chapter 1 provides a literature overview of tooth-replacing fiber-reinforced fixed partial dentures. Material properties and material design factors of fiber-reinforced material are described. After consideration of limitations in performance of these kind of restorations, in particular for the anterior area, the objectives and outline of this thesis are described. The general objectives of the present thesis were to address the behavior of fiber-reinforced material in adhesive bridges and to investigate the performance of resin-bonded FRC FPDs as a viable alternative to metal resin- bonded FPDs as a (semi) permanent construction in the anterior region.

A systematic literature review is presented in **Chapter 2**. The purpose of this study was to aggregate literature data on in vitro three-point bending tests of fiber-reinforced composite (FRC) beams, with regard to studies that followed criteria described in an International Standard. The reported reinforcing effects of various fibers on the flexural strength and elastic modulus of composite resin beams were analyzed. Original, peer reviewed papers, selected using Medline from 1950 to 2007, on in vitro testing of FRC beams in comparison to non-reinforced composite beams. Also information from conference abstracts (IADR) was included. With the keywords (fiber or fibre) and (resin or composite) and (fixed partial denture or FPD), the literature search revealed 1427 titles. Using this strategy a broad view of the clinical and non-clinical literature on fiber-reinforced FPDs was obtained. Restricting to three-point bending tests, seven articles and one abstract were included. Finally, the data of 363 composite beams were analyzed. The differences in mean flexural strength and/or modulus between reinforced and unreinforced beams were set out in a forest plot. Meta-regression analyses were performed (single and multiple regression models). It was concluded that under specific conditions fibers do reinforce resin composite beams. The flexural modulus not always seems to increase with one type of fibers, even when fibers are located at the tensile side. Besides, fiber architecture (woven vs. unidirectional) seems to be more important than the type of fiber for flexural strength and flexural modulus.

In the past decade follow-up studies on FRC FPDs have been described. **Chapter 3** presents a structured literature review on clinical studies on FRC FPDs. The objective of this systematic review was to obtain survival rates of FRC FPDs and to explore relationships between reported survivals and risk factors. In a literature selection procedure fifteen studies, reporting on 13 sets of patients, on the clinical performance of FRC FPDs were analyzed. The results of this study based on the data from all sets of patients (n=435) showed an survival of 72.3 (CI 68.3-76.3)% at 4.5 years. Converted survival rates at 2 year follow-up showed substantial heterogeneity between studies. It was not possible to build a reliable regression model that indicated risk factors. Most described technical problems were fracture of the FPD and delamination of the veneering composite.

A retrospective study on the clinical performance of anterior FRC FPDs is described in **Chapter 4.** The purpose of this clinical study was to evaluate the long-term outcome of three-unit anterior FPDs made of fiber-reinforced resin composite (FRC), and to identify design factors influencing the survival rate. Fifty-two patients (26 females, 26 males) received 60 indirectly made FRC FPDs, using pre-impregnated unidirectional glass-fibers, requiring manual wetting, as framework material. FPDs were surface (n=48) or hybrid (n=12) retained and mainly located in the upper jaw. Hybrid FPDs had a combination of retainers; i.e. crown at one and surface retention at the other abutment tooth. Surface FPDs were either purely adhesively retained (n=29) or with additional mechanical retention (n=19). Follow-up period was at minimum 5 years, with check-ups every 1-2 years. Six operators were involved, in three centers in the Netherlands, Finland and Sweden. Survival rates, including repairable defects of FPDs, and succes rates were determined. Survival rate at 5 years was 64 ± 7%. For the level of success, values were and the estimated median survival time 58 ± 10.1% months. For surface FPDs, additional mechanical retention did not improve survival significantly. Main failure modes were fracture of the FPD and delamination of veneering composite, especially for surface FPDs.

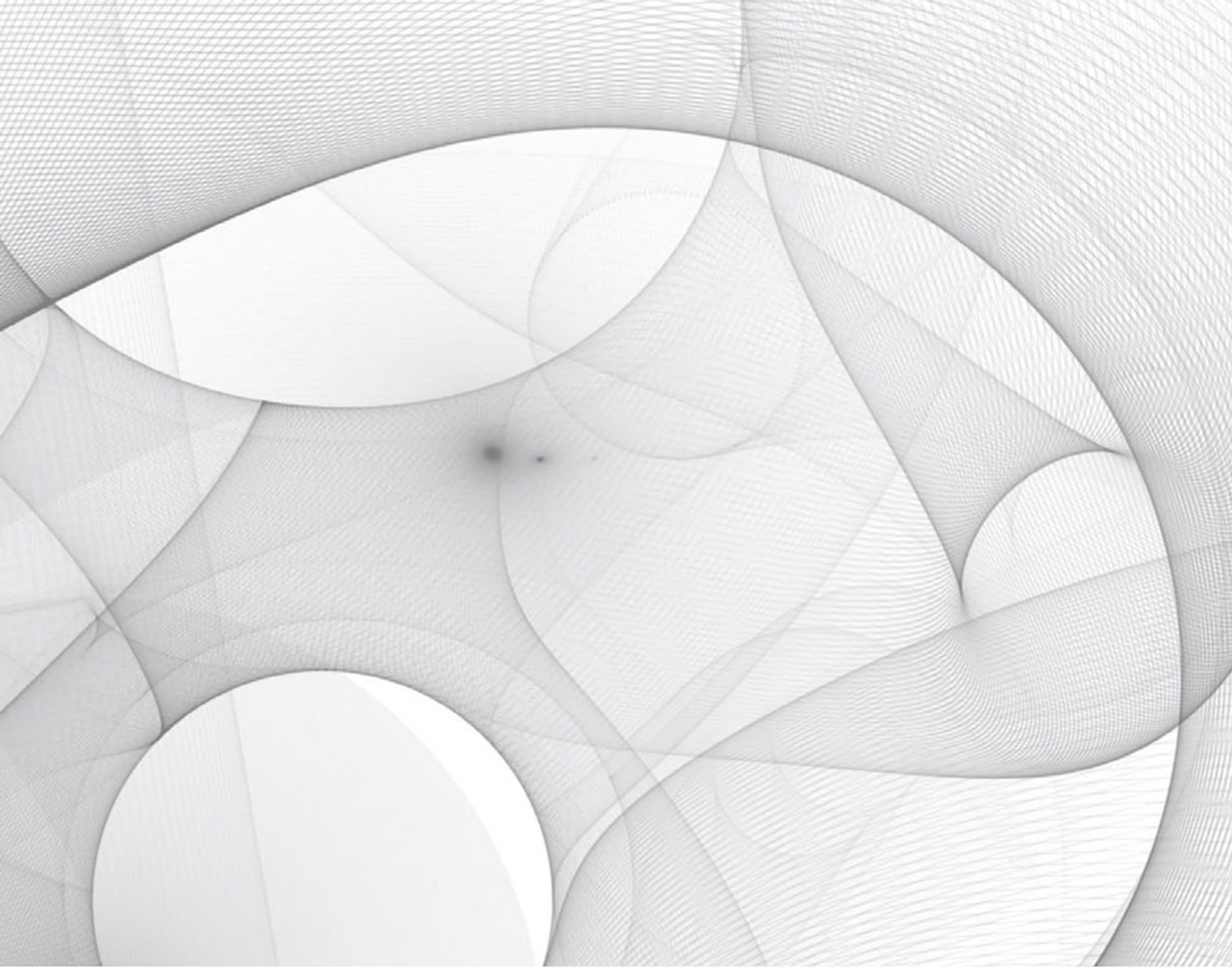
Chapter 5 presents another restrospective clinical study. The purpose of this clinical study was to evaluate the long-term outcome of three-unit posterior FPDs made of fiber-reinforced resin composite (FRC), and to identify design factors influencing the survival rate. Seventy-seven patients (52 females, 25 males) received 96 indirectly made FRC FPDs, using pre-impregnated unidirectional glass-fibers, requiring manual wetting, as framework material. FPDs were surface (n=31) inlay (n=45) or hybrid (n=20) retained and mainly located in the upper jaw. Hybrid FPDs consisted of a wing retainer at canine and an inlay retainer at distal abutment tooth. Surface FPDs consisted of uplay and wing combinations. Follow-up period was at minimum 4.5 years, with check-ups at every 1-2 years. The study was carried out by 6 operators in three centers in the Netherlands, Finland and Sweden. Survival rates, including reparable defects of FPDs, and success rates were determined. Survival rate at 5 years was 71.2 ± 4.8% for success and 77.5 ± 4.4% for survival. Survival rates of inlay, hybrid and surface retained FPDs did not significantly differ. Main failure modes were delamination and fracture of the FPD. Only FPDs with surface retainers showed debonding.

From the results of the clinical study, it can be advocated to redirect laboratory study design for testing a bridge construction with clinically relevant applied forces and valid construction models. Therefore, a laboratory simulation of a clinically failed anterior FRC FPD was described in **Chapter 6.** The standard method for laboratory testing of fiber-reinforced materials is the three-point bending test. The purpose of this study was to develop a test design that supports new developments in FRC framework design. Therefore, the loading conditions of a typical failure mode of an FRC FPD as most commonly seen in the anterior area was simulated. Case simulation of a three-unit FRC FPD with a Maryland design with two surface retainers was performed in a universal testing machine. Testing was performed in 3 groups. (1) Static loading of the FPD at the occlusal contact points (retainers and pontic) and in the same direction as in the clinical situation. (2) Static loading at the pontic only, to simulate overloading. (3) Dynamic loading of the FPD as in (1). Examination of the fractured restorations was performed by SEM. Fractures, delamination and crack formation, specifically in the retainer area, as seen in the clinical situation were observed in the laboratory situation as well. The present results suggests that this new laboratory method can be valid for further development studies into the design of FRC FPDs in the anterior area.

Finally, **Chapter 7** discussed the findings of the different parts of this study in summary and the relations between the results. The main questions (as formulated in the General Introduction) are discussed related to the studies performed in this thesis. The limitations of different studies and their results are discussed. Recommendations for future research were formulated and finally conclusions were given.
Related to the general objectives, this thesis suggest that:

- Under specific conditions it has been shown that fiber reinforcement has a beneficial effect on *in vitro* fracture resistance. However, the strengthening effect regarding flexural modulus is limited to the type of fibers. Besides, fiber architecture seems to be more important for the reinforcement of the resin material than the type of fiber.

- o From both literature studies and clinical retrospective studies it has been shown that the survival probability of FRC FPDs in the posterior area is higher than restorations in the anterior area. Main failure modes consisted of delamination of the veneering composite and fracture of the framework. However, delamination of the anterior FPDs mainly concerned the retainers, while in the posterior FPDs it was the pontic area.
- o There is no difference in clinical survival of different types of FPD (surface vs hybrid vs inlay retained FPDs) in the anterior as well as posterior area. Differences in survival percentages of surface FPDs with or without additional mechanical retention in the anterior area were not statistically different.
- o It is shown that the retainer and connector area for anterior FRC FPDs are predominantly affected at failure. This suggests further development of the framework design is required. For variations of the design of anterior FPDs a clinically relevant test set-up is needed. It has been shown to be possible to develop a clinically relevant laboratory set-up. Further research is needed.



Chapter 9

Samenvatting

Dit proefschrift richt zich op de gedragingen in de kliniek en in het laboratorium van adhesief bevestigde vezelversterkte composietbruggen, met name op het gebied van fronttandvervanging. Op dit moment is er geen eenduidige richtlijn voor het optimale ontwerp van het frame van composietbruggen in het front met vezelversterking, wat de algemeen practicus terughoudend maakt bij het gebruik van vezelversterkt composiet. Toch kan de toepassing van adhesiefbruggen van vezelversterkt composietmateriaal een interessant alternatief zijn in vergelijking met conventioneel brugwerk en metaalporseleinen adhesiefbruggen, waarbij de minimaal invasieve tandheelkunde in acht wordt genomen.

Hoofdstuk 1 beschrijft een literatuuroverzicht over tandvervangende vezelversterkte composiet brugconstructies. Factoren met betrekking tot materiaaleigenschappen en materiaal ontwerp van vezelversterkt composiet worden beschreven. De vragen en kaders waarin dit onderzoek is uitgevoerd worden beschreven, nadat de beperkingen van de toepassing van dit type restauraties, met name voor het frontgebied, zijn benoemd. De algemene onderwerpen in dit proefschrift zijn het gedrag van het vezelversterkt materiaal in adhesiefbruggen en het gedrag van vezelversterkte composietbruggen zelf, als alternatief voor metaalporselein adhesiefbruggen als (semi)permanente constructie in het frontgebied.

Een gestructureerd literatuur onderzoek met betrekking tot laboratorium onderzoek naar vezelversterking in composietbalken wordt gepresenteerd in **Hoofdstuk 2**. Het doel van deze studie was om *in vitro* gegevens van driepuntsbuigproeven met vezelversterkte composietbalken uit de literatuur te verzamelen, waarbij gekeken is naar studies die de ISO standaard volgden. De beschreven versterkende effecten van verschillende typen vezels op de buigsterkte en elasticiteitsmodulus van composietbalken werden geanalyseerd. Een digitale database (Medline) werd gebruikt om Engelstalige tandheelkundige artikelen te zoeken van 1950 tot en met 2007, met betrekking tot *in vitro* onderzoek naar vezelversterkte composietbalken vergeleken met onversterkte balken. Ook informatie uit conference abstracts (IADR) werd inbegrepen. Met de gebruikte trefwoorden: "(fiber or fibre) and (resin or composite) and (fixed partial denture or FPD)", werden 1427 referenties gevonden. Door deze strategie toe te passen werd een brede selectie van de klinische en niet-klinische literatuur over vezelversterkt composietmateriaal verkregen. Beperking van het zoekresultaat tot driepuntsbuigproeven leverde 7 artikelen en 1 abstract. De gegevens van 363 composietbalken zoals beschreven in de studies werden geanalyseerd. De verschillen in gemiddelde buigsterkte en/of elasticiteitsmodulus tussen versterkte en onversterkte composiet balken werden weergegeven in een forest plot. Vervolgens werden meta-regressie analyses uitgevoerd (enkele en multiple regressie modellen). Geconcludeerd werd dat onder specifieke omstandigheden composietbalken worden versterkt door de toepassing van vezels. Door één type vezel werd de elasticiteits-modulus niet altijd verbeterd, zelfs niet als de vezels werden aangebracht aan de trekzijde van de balk. Daarnaast bleek voor zowel buigsterkte als elasticiteitsmodulus dat de vezelarchitectuur (geweven versus unidirectioneel) belangrijker leek te zijn dan het type vezel.

Pas sinds het afgelopen decennium zijn follow-up studies naar vezelversterkte composietbruggen beschreven. **Hoofdstuk 3** beschrijft een gestructureerd literatuur onderzoek naar klinische studies met betrekking tot vezelversterkte composiet-bruggen. Het doel van dit gestructureerd literatuuronderzoek was het verkrijgen van een gemiddelde levensduur van vezelversterkte composietbruggen en het onder-zoeken van relaties tussen beschreven risicofactoren en overlevingspercentages. Er werden 15 studies met betrekking tot het klinische gedrag van vezelversterkte composietbruggen geanalyseerd. Deze studies beschreven samen 13 patiënten-populaties met in totaal 435 bruggen. Er werd een overlevingspercentage berekend van 72.3 (CI 68.3- 76.3)% na 4,5 jaar. Reconstructie van de survivalpercentages na 2 jaar follow-up liet zien dat er een zekere heterogeniteit bestaat tussen de studies. Het was niet mogelijk een betrouwbaar regressie model te maken waarmee risicofactoren konden worden aangetoond. De meest beschreven technische problemen waren complete breuk van de brugconstructie en delaminatie van het veneercomposiet.

Een retrospectief onderzoek naar het klinisch gedrag van vezelversterkt composiet in het frontgebied wordt in **Hoofdstuk 4** beschreven. Het doel van deze klinische studie was het evalueren van het langetermijn functioneren van driedelige frontbruggen van vezelversterkt composiet en het inventariseren van ontwerpfactoren die de levensduur beïnvloeden. Bij 52 patiënten (26 vrouwen, 26 mannen) werden 60 indirect vervaardigde vezelversterkte composietbruggen geplaatst. Hierbij werd handmatig gepreïmpregneerd unidirectioneel glasvezelmateriaal gebruikt als onderstructuur. Er was sprake van oppervlakte retentie door middel van retentiegroeven en stops (n=48) of hybride retentie (n=12) en de bruggen waren met name in de bovenkaak geplaatst. Hybride retentie betekende een combinatie van retainers; bijvoorbeeld een kroon op de ene pijler en oppervlakte retentie aan de andere pijler. Bruggen waarbij gebruik werd gemaakt van oppervlakte retentie konden worden verdeeld in zuiver adhesief bevestigde bruggen (n=29) of met aanvullende mechanische retentie (n=19). De follow-up periode was minimaal 5 jaar, met controles iedere 1-2 jaar. Er waren 6 behandelaars betrokken, in 3 centra in Nederland, Finland en Zweden. Er werd een onderscheid gemaakt tussen overlevingskansen, waarbij eventuele reparaties van bruggen werden geaccepteerd, en de kans op succes in de originele staat. Het overlevingspercentage na 5 jaar was 64 ± 7% en voor 'succes' was dat 45 ± 7%. De berekende mediaan voor de levensduur was 58 ± 10.1% maanden. Voor bruggen met oppervlakte retentie bleek dat aanvullende mechanische retentie de overlevingskansen niet significant verbeterde. Belangrijkste redenen voor falen waren breuk van de brug en delaminatie van het veneer composiet, met name voor bruggen met oppervlakte retentie.

Hoofdstuk 5 beschrijft eveneens een retrospectief klinisch onderzoek. Het doel van deze studie was het evalueren van het langetermijn functioneren van driedelige bruggen in de zijdelingse delen van vezelversterkt composiet, en het inventariseren van ontwerpfactoren die de levensduur beinvloeden. Bij 77 patienten (52 vrouwen, 25 mannen) werden 96 indirect vervaardigde vezelversterkte composietbruggen geplaatst. Hierbij werd handmatig gepreïmpregneerd unidirectioneel glasvezel-materiaal gebruikt als onderstructuur. Er was sprake van oppervlakte retentie (n=31), retentie in de vorm van een inlay (n=45), of hybride retentie (n=20) en de bruggen waren met name in de bovenkaak geplaatst. Hybride bruggen bestonden uit retentie in de vorm van een vleugel op de hoektand en een inlay restauratie in het distale pijlerelement. Bruggen met oppervlakte retentie bestonden uit combinaties van retainers in de vorm van uplay restauraties en vleugels. De follow-up periode was minimaal 4,5 jaar, met controles iedere 1-2 jaar. Er waren 6 behandelaars betrokken, in dezelfde setting als beschreven in hoofdstuk 4. Er werd een onderscheid gemaakt tussen overlevingskansen, waarbij eventuele reparaties van bruggen werden geaccepteerd, en de kans op succes in de originele staat. Het overlevingspercentage na 5 jaar was 77.5% ± 4.4% en voor 'succes' was dat 71.2 ± 4.8%. Er werden geen significante verschillen gevonden in overleving van de verschillende typen bruggen. Belangrijkste redenen voor falen waren delaminatie en breuk van de brug. Loskomen van de brug werd enkel gezien bij bruggen met oppervlakte retentie.

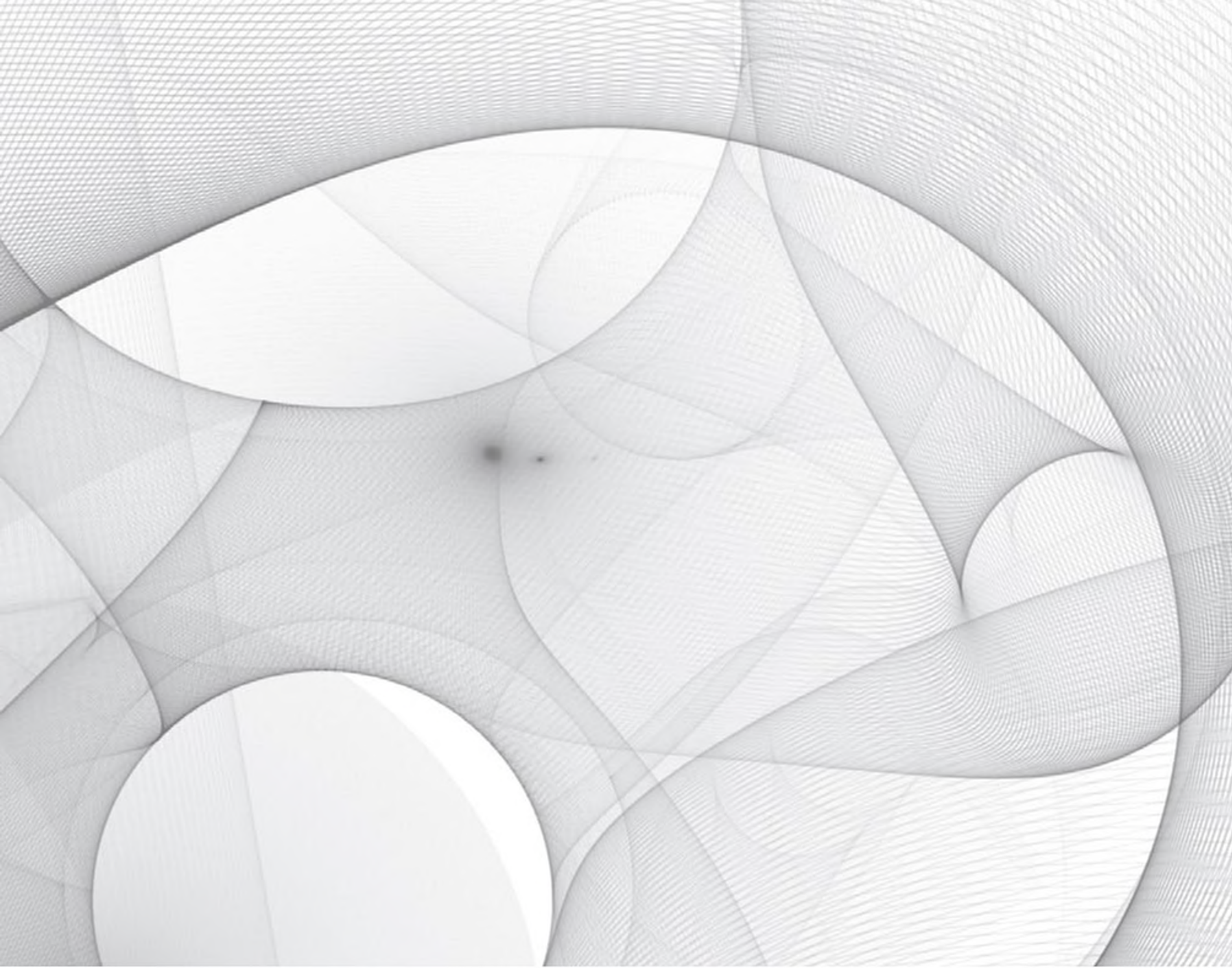
Aangezien het klinische falen zoals beschreven in dit proefschrift niet kan worden voorspeld uit de huidige laboratorium proeven, is het zinvol om een nieuw model voor laboratoriumonderzoek te ontwikkelen. Daarom wordt in **Hoofdstuk 6** een laboratorium simulatie beschreven van een gefaalde anterior vezelversterkte composietbrug in een klinische situatie. De standaard methode om vezelversterkte materialen te testen is de driepuntsbuigproef. Het doel van deze studie was het ontwikkelen van een testopzet waarin het ontwerp van de onderstructuur van een brugconstructie onderzocht kan worden. Hiertoe is de wijze van belasten bij het typisch faalgedrag van een vezelversterkte composietbrug in het frontgebied nagebootst. In een universeel testapparaat is een casus gesimuleerd met een driedelige vezelversterkte composietbrug van het type 'Maryland' (met oppervlakte retentie aan beide zijden). De tests zijn uitgevoerd in 3 groepen. (1) Statische belasting van de brug op de occlusale contactpunten (op retainers en pontic) in dezelfde richting als in de klinische situatie. (2) Statische belasting op de pontic alleen om overbelasting te simuleren. (3) Dynamische belasting van de brug op dezelfde wijze als in (1). Bestudering van de gefractureerde restauraties werd uitgevoerd middels SEM. Net als in de klinische situatie waren fracturen, delaminatie en cracks te zien in de laboratorium situatie, met name in het retainer gedeelte. De resultaten van deze studie laten zien dat deze nieuwe opzet in het laboratorium waardevol kan zijn voor verdere ontwikkeling van het ontwerp van vezelversterkte composietbruggen in het frontgebied.

Tot slot worden in **Hoofdstuk 7** de bevindingen van de verschillende onderzoeken in relatie tot elkaar beschreven. De hoofdvragen (zoals in de algemene inleiding beschreven) worden bediscussieerd aan de hand van onderzoeken die voor dit proefschrift zijn uitgevoerd. De beperkingen van de verschillende deelonderzoeken en de resultaten worden besproken. Verder worden er aanbevelingen gedaan voor toekomstig onderzoek en conclusies worden getrokken.
In relatie tot de algemene onderzoeksvragen wordt geconcludeerd dat:

- Vezelversterking heeft, onder specifieke omstandigheden, een positief effect op de *in vitro* breukweerstand. Echter, het positieve effect op de elasticiteitsmodulus is afhankelijk van het type vezel. Daarnaast blijkt de vezelarchitectuur belangrijker te zijn voor de versterking van het composiet materiaal dan het type vezel.
- Zowel uit literatuur studies als klinisch retrospectief onderzoek is aangetoond dat de overlevingskans van vezelversterkte composietbruggen in de zijdelingse delen hoger is dan restauraties in het frontgebied. Belangrijkste redenen voor falen bestonden uit delaminatie van het veneer composiet en complete breuk van de onderstructuur van de constructie. In het frontgebied betrof delaminatie echter vooral de retainers, terwijl dat bij de bruggen in de zijdelingse delen met name de pontic betrof.
- Er is geen verschil gevonden in de klinische overleving van verschillende types bruggen (oppervlakte retentie vs hybride vs inlay retentie), zowel voor het

frongebied als de zijdelingse delen. Er was geen significant verschil in overlevingspercentages tussen de groepen met of zonder aanvullende mechanische retentie bij de frontbruggen met oppervlakte retentie.

- Uit dit onderzoek komen sterke aanwijzingen dat met name het retainer en connector gedeelte van vezelversterkte composietbruggen in het front zijn aangedaan bij falen van de constructie. Dit strekt tot aanbeveling om het ontwerp van de onderstructuur verder te ontwikkelen. Om variaties in het ontwerp van frontbruggen te kunnen onderzoeken, is een relevante test opzet nodig. Het bleek mogelijk om een klinisch relevante laboratorium opzet te ontwikkelen. Verder onderzoek is nodig.



Dankwoord

Curriculum Vitae

Publications

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