Exploring the limitations of fibre-reinforced composite fixed dental prostheses: Fibres (un)limited
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CHAPTER 2

Fracture strength and fatigue resistance of dental resin-based composites
2.1 Abstract

Objectives: The aim of this study was to evaluate in vitro the influence of fibre-reinforcement on the fracture strength and fatigue resistance of resin-based composites.

Materials and Methods: One hundred rectangular bar-shaped specimens (2 x 2 x 25 mm) made of resin-based composite were prepared in a stainless steel split-mould: (i) thirty specimens of particulate filler composite (PFC) (Filtek Z100, 3M ESPE, St Paul, MN, USA), (ii) thirty specimens of fibre-reinforced composite (FRC) (everStick C&B, Sticktech Ltd, Turku, Finland) and (iii) forty specimens of PFC and FRC combined in two longitudinal layers of equal thickness. Each specimen was trimmed into a cylindrical hourglass shape. The fracture strength (cantilever beam test, n = 10) and the fatigue resistance (rotating cantilever beam test; staircase method: 10⁴ cycles, 1.2 Hz, n = 20) were determined. Fracture strength, fatigue resistance and work-of-fracture were calculated. The fracture surfaces of failed specimens were analysed with SEM. Data was analyzed by logistic regression, one-way ANOVA followed by Tukey’s post hoc test and, a student t-test.

Results: ANOVA revealed that fibre-reinforcement had significant effect (p < 0.001) on fracture strength, fatigue resistance, and work-of-fracture. Student t-test showed significant differences (p <0.001) in fatigue resistance compared to fracture strength.

Conclusions: Within the limitations of this study, the following conclusions can be drawn (i) the fatigue resistance of resin-based composites is lower than their fracture strength and (ii) FRC are more fatigue resistant than PFC or combinations of FRC and PFC.
2.2 Introduction

The use of resin-based composites increased enormously during the last two decades. Their increasing popularity could be attributed to the paradigm shift from G.V. Black’s “extension for prevention” [1] to minimal invasive dentistry [2] established by the development of adhesive dentistry. The adhesive revolution and subsequent popularity of resin-based composites was initiated by two major breakthroughs: the introduction of the acid etch technique by Buonocore in the mid 1950s [3] and the development of Bis-GMA as an organic matrix for resin composites by Bowen in the early 1960s [4]. When considering resin-based composites one should keep in mind that this in fact represents a composite family consisting of, among others, particulate filler composites and fibre-reinforced composites, being the subject of the present study.

The range of indications where resin-based composites in general and particulate filler composites (PFC) in particular are used has expanded explosively due to their enhanced physical and mechanical properties. Today, resin-based composites are indicated on a regular basis for posterior direct and laboratory made restorations, as an extension to their original indication which was limited to direct restorations in anterior teeth. After the introduction of fibre-reinforced composites (FRC) and especially the development of glass fibre-reinforced composites [5], resin-based composites came into focus as a material that has the capabilities to be used for the fabrication of fixed dental prosthesis (FDP). In order to be able to withstand the chewing forces, resin-based composite FDPs are made of a FRC-framework veneered with PFC, with FRC acting as a stress dissipater while the PFC gives the construction its aesthetic properties. This type of prosthetic constructions is known in literature as fibre-reinforced composite fixed dental prostheses (FRC-FDPs). The growing interest in this type of restorations was stimulated by the high demand for improved aesthetics and by the growing concerns related to metallic restorations [6].

In spite of the less favourable longevity exhibited by cantilever FDPs in comparison to fixed-fixed FDPs [7,8], there is still a persistent need for this treatment option. The mostly used indication for cantilever FDPs is for extending a shortened dental arch. Also in the field of resin-bonded FDPs a two-unit cantilever design can be a viable alternative that has proven to perform as well as or even better than their three-unit fixed-fixed counterparts [9-11]. The clinical success of two-unit cantilever resin-bonded FDPs led to the use of resin-based composites for the fabrication of these restorations. Two-unit cantilever resin-bonded FRC-FDPs are already used for single
tooth replacement in the anterior region [12-14] and maybe in the future also in the posterior region [15].

Dental restorations during clinical functioning are not only subjected to high static loads, but also to low cyclic loads, the latter known as fatigue loading. Fatigue is a mode of failure whereby cracks are induced by subjecting a material or structure to repeated sub-critical loads, which leads eventually to failure [16]. Mechanical failure of dental restorations can be attributed in the majority of the cases to fatigue loading, which makes fatigue resistance one of the most important and clinically relevant properties of a dental material or restoration [16]. Little information about the fatigue resistance of fibre-reinforced composites used in dentistry is available at the moment [17-20]. The forces occurring during physiological function have a vertical as well a horizontal component, which make them multi-vectorial in nature [21]. A representative laboratory test should cope with both aspects, which can be accomplished by means of a rotating cantilever beam fatigue test [16].

The aim of this study was to evaluate in vitro the influence of fibre-reinforcement on the fracture strength and fatigue resistance of resin-based composites. The fracture strength was obtained by means of a cantilever beam test, while the fatigue resistance was obtained according to the staircase approach in a rotational cantilever beam fatigue testing device. The null hypothesis to be tested in this experiment was that a fibre-reinforced composite exhibited a comparable fatigue resistance as a particulate filler composite.

2.3 Materials and Methods

Table 2.1 Materials used in the study.

<table>
<thead>
<tr>
<th>Brand</th>
<th>Composition</th>
<th>Manufacturer</th>
<th>Lot number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filtek Z100</td>
<td>Resin: Bis-GMA, TEGDMA; Filler: zirconia, silica (≈ 64.2 vol%)</td>
<td>3M-ESPE Dental products, St Paul, MN, USA</td>
<td>70-2010-2226-9</td>
</tr>
<tr>
<td>everStick C&amp;B</td>
<td>Resin: PMMA, Bis-GMA; Filler: silanised E-glass fibres (≈ 65 vol%)</td>
<td>Sticktech Ltd., Turku, Finland</td>
<td>2070212-ES-179</td>
</tr>
</tbody>
</table>

Bis-GMA bisphenol-A-glycidyl dimethacrylate; TEGDMA triethylenglycol dimethacrylate; PMMA poly(methyl methacrylate).

Two resin-based composites, i.e. one particulate filler composite (PFC) (Filtek Z100, 3M ESPE, St Paul, MN, USA) and one fibre-reinforced composite (FRC) (everStick C&B, Sticktech Ltd, Turku, Finland), both within their field of application widely used and Bis-GMA-based materials, were selected for this experiment.
EverStick C&B was delivered as prepregs containing 4000 continuous unidirectional silanised E-glass fibres (≈ 65 vol%) of 21 μm in diameter impregnated with light polymerisable semi-interpenetrating polymer network of PMMA/Bis-GMA resin. The composition of the materials used is summarised in Table 2.1.

**Specimen preparation**

One hundred rectangular bar-shaped specimens (2 x 2 x 25 mm) made of resin-based composite were prepared in a stainless steel split-mould. Thirty specimens were made of PFC, thirty specimens were made of FRC and forty specimens were made of a combination of FRC and PFC in two longitudinal layers of equal thickness.

To prepare the specimens the mould was filled in bulk with a resin-based composite (PFC, FRC or a bilayer of FRC and PFC) and covered on both sides with a cellophane sheet and a slide glass. In order to fabricate bilayered specimens with layers of equal thickness, the mould was first filled with a 1 mm thick layer of FRC and subsequently the mould was completely filled by adding PFC. The thickness of the FRC layer was checked with a Teflon space maintainer. The specimens were light cured for 60 s (3 x 20 s overlapping irradiation) on each side by a handheld polymerization unit (Astralis 10, Ivoclar-Vivadent, Schaan, Liechtenstein) with a power output of 1000 mW·cm⁻² (Curing Radiometer model 100, Demetron Research Corporation, Danbury, USA).

The specimens were mounted in a lathe cutting machine (Micro miller MF 70, Proxxon GmbH, Niersbach, Germany) and trimmed under continuous water-cooling at one-third of their length into a cylindrical hourglass shape with a diameter of 1.2 ± 0.1 mm using a tungsten carbide bur (H79EF.104.040, Komet, Lemgo, Germany). The diameter of the hourglass-shaped constriction was measured by a laser micrometer (Laser Scan Micrometer LSM 6000/LSM 503, Mitutoyo, Kawasaki, Japan). All specimens were stored in 37°C distilled water for at least 72 h until testing.

**Fracture strength**

The fracture strength was obtained by subjecting the specimens (n = 10) to a cantilever beam test (Figure 2.1A). Bar specimens were fixed in a custom-made device in a way the clamps bordered the hourglass shape. Four groups of 10 specimens each were tested:

1. PFC: specimens made of PFC only.
2. FRC: specimens made of FRC only.
3. FRC-t: bilayer specimens made of a combination of PFC and FRC, where the FRC is placed at the tension side of the specimens.
4. FRC-c: bilayer specimens made of a combination of PFC and FRC, where the FRC is placed at the compression side of the specimens. 

The load was applied at a distance of 10 mm from the hourglass-shaped constriction by a steel rod. The specimens were loaded till failure in a universal testing machine (Hounsfield 12B AD, model 20-30, Salfords, UK) at a cross-head speed of 0.5 mm·min⁻¹ and data were recorded by PC software (ACTA inTense 3.15, ACTA, Amsterdam, the Netherlands).

The fracture strength \( S \) (MPa) of the first two groups, which were made of only one material, was calculated with the formula found in most textbooks on engineering science \[22\]:

\[
S = \frac{32Fl}{\pi d^3}
\]  

(1)

The load \( F \) (N) multiplied by the distance \( l \) (10 mm) between the point of loading and the hourglass constriction represent the applied moment, and \( d \) (mm) is the smallest diameter of the constriction.

Because of the different elastic modules of the bilayer groups (FRC-t and FRC-c) the neutral line \[22\] is not at the centre of the cross-section and therefore equation 1 cannot be used. The shift of the neutral line \( n \) (mm) relative to the centre of the cross-section is calculated as

\[
n = \frac{2d}{3\pi} \cdot \frac{1 - R}{1 + R}
\]  

(2)

\( R = \frac{E_c}{E_t} \), is the ratio between the elastic moduli of the materials of the compressive and tensile layers respectively. Because assessment of the elastic modulus more or less requires complex finite element analysis modelling and as only the ratio between these is used, the ratio \( (R) \) may be found with

\[
R = \frac{E_c}{E_t} = \frac{F_c \cdot l^2_t}{D_c \cdot d^4_c} \cdot \frac{D_t \cdot d^3_t}{F_t \cdot l^2_t}
\]  

(3)

This equation uses the stiffness of one-material rods \( (F/D) \) to compare the moduli with a correction for the position \( (l) \) and diameter \( (d) \) of the constriction, where most of the bending occurs. With these definitions, the strength on the tensile side becomes
\[ S = 192 \cdot F \cdot L \cdot \frac{d - 2n}{3 \pi d^4 - 64nd^3 + 48n^2d^2 + R \cdot (3 \pi d^4 + 64nd^3 + 48n^2d^2)} \] (4)

With equal modules \( E_t \) and \( E_c \), \( R \) becomes 1, equation 2 returns \( n = 0 \) and equation 3 simplifies to equation 1. If the maximum compression on the opposite side is of interest, equation 3 is multiplied by \(-R\) and the minus sign in the numerator is replaced with a plus \( (d+2n) \).

**Figure 2.1** Schematic representation of (A) the cantilever beam test and (B) the rotating cantilever beam fatigue testing device: specimens are rotating around their longitudinal axis and loaded by attaching a weight \( (F) \) to a ball-bearing.
**Work-of-fracture**

The load-displacement curves were used to calculate work-of-fracture ($\gamma_{\text{WoF}}$, kJ·m$^{-2}$) is the energy required to fracture a specimen and is calculated by dividing the area under the load-displacement curve by the specimen’s cross-sectional area:

\[
\gamma_{\text{WoF}} = \frac{4A}{\pi d^2}
\]  

Where $A$ (N·mm) is the area under the load-displacement curve and $\frac{1}{4} \pi d^2$ is the area of the cross-section (mm$^2$).

**Fatigue resistance**

The fatigue resistance of resin-based composites was determined by using a rotating cantilever beam fatigue testing device (Figure 2.1B). The specimens ($n = 20$) for each group; PFC, FRC, and FRC-PFC, respectively) were mounted in the chuck of the fatigue device. A ball-bearing was fixed to the beams at a distance of 10 mm from the hourglass constriction. The stress at the smallest diameter of the constriction was induced by attaching a weight onto the ball-bearing. The required force ($F$) was calculated with equation 1.

The “staircase” or “up-and-down” method was used as the analytical method for this experiment. Within each group of specimens the initial stress was set at ca. 50% of the previously determined fracture strength for all groups. The specimens were rotated at 1.2 Hz for $10^4$ cycles or until failure. If failure occurred before $10^4$ cycles the stress was decreased with 7.5% of the original fracture strength, respectively increased with the same percentage when the specimen survived.

**Fibre volume fraction**

The fibre volume fraction of each test group was determined by the resin burn-off method. The weight of the specimens ($n = 3$) was measured (Mettler AT261; Mettler Instrument, Highstone, NJ, USA) before and after combustion of the resin matrix for 1 h at 700ºC. The particulate fillers were mechanically removed. The fibre volume fraction $V_f$ in vol % was calculated with the following formula:

\[
V_f = \left(\frac{W_f}{\rho_f}\right)\left(\frac{W_f}{\rho_f} + (1 - W_f)/\rho_r\right)
\]  

where $W_f$ is the weight proportion of the fibres, $\rho_f$ the density of the fibres (E-glass = 2.54 g·cm$^3$) and $\rho_r$ the density of the resin matrix (everStick resin = 1.22 g·cm$^3$).
Fatigue of resin composites

Failure mode

All fractured specimens were visually examined and inspected under a light microscope (4 x magnification). A number of representative specimens (cantilever beam test: n = 3; rotating cantilever fatigue test: n = 6) were gold sputtered (Edwards Sputter Coater S150B, Edwards High Vacuum, Crawley, West Sussex, England) and their fracture surface was examined by scanning electron microscopy (Philips XL 20, Eindhoven, the Netherlands).

Statistical Analysis

Statistical analysis was performed with the statistical software SigmaStat 3.0 (SPSS Inc. Chicago, IL, USA). The dataset obtained from the fatigue test was analyzed using logistic regression in order to determine the fatigue resistance and standard deviation. The fatigue resistance can be defined as the load at which the probability of failure is 50%. Means and standard deviations of fracture strength, work-of-fracture and fatigue resistance for each group were calculated (Table 2.2). One-way analysis of variance (ANOVA) followed by Tukey’s post hoc test were performed to determine the effect of fibre-reinforcement on the observed fracture strength, work-of-fracture and fatigue resistance. P-values of less than 0.05 were considered to be statistically significant. A student t-test was performed to compare the effect of fatigue testing and fracture testing.

2.4 Results

The mean fracture strength, fatigue resistance, work-of-fracture and fibre volume fraction of each experimental group are summarised in Table 2.2.

One-way ANOVA revealed significant differences in fracture strength (F = 111.9; p < 0.001), work-of-fracture (F = 33.1; p < 0.001), and fatigue resistance (F = 436.7; p < 0.001) of hourglass-shaped specimens made of different resin-based composites.

The highest fracture strength, work-of-fracture and fatigue resistance were obtained for FRC bars. Specimens made of a combination of FRC and PFC showed the second highest fracture strength and work-of-fracture when the FRC was placed in tension (FRC-t). There was no significant difference regarding fracture strength and work-of-fracture between PFC bars and FRC-PFC combination bars when the FRC was placed in compression (FRC-c).
Student t-test showed statistically significant differences in fatigue resistance compared to fracture strength of hourglass-shaped specimens made of PFC ($t = 9.3; p < 0.001$), FRC ($t = 14.7; p < 0.001$) and bilayered specimen with FRC in tension ($t = 50.7; p < 0.001$).

Table 2.2  Mean fibre volume fraction, fracture strength, fatigue resistance, work-of-fracture and, ratio between fracture strength and fatigue resistance, with SD in parentheses, of resin-based composites. Test groups with the same superscript letter are not statistically different.

<table>
<thead>
<tr>
<th>Group</th>
<th>Fibre volume fraction (vol %)</th>
<th>Fracture strength (MPa)</th>
<th>Fatigue resistance (MPa)</th>
<th>Work-of-Fracture (kJ·m$^{-2}$)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFC</td>
<td>0</td>
<td>164.9$^{a}$ (29.7)</td>
<td>51.5$^{d}$ (32.3)</td>
<td>0.55$^{B}$ (0.19)</td>
<td>0.32</td>
</tr>
<tr>
<td>FRC-t</td>
<td>16</td>
<td>539.5$^{b}$ (35.2)</td>
<td>116.5$^{a}$ (9.9)</td>
<td>14.20$^{C}$ (2.21)</td>
<td>0.15</td>
</tr>
<tr>
<td>FRC-c</td>
<td>125.2$^{a}$ (38.0)</td>
<td>116.5$^{a}$ (9.9)</td>
<td>14.20$^{C}$ (2.21)</td>
<td>0.21$^{B}$ (0.13)</td>
<td>0.95</td>
</tr>
<tr>
<td>FRC</td>
<td>42</td>
<td>936.1$^{c}$ (218.5)</td>
<td>231.9$^{e}$ (2.9)</td>
<td>27.90$^{D}$ (14.17)</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Failure mode

SEM examination of the broken specimens demonstrated that PFC bars failed from a critical crack (point of highest stress concentration) that was located at the periphery of the beams (Figure 2.3A). These specimens revealed an elastic behaviour and were associated with an immediate drop in load once the ultimate strength was reached, defined as instantaneous failure (Figure 2.2C) [23]. The highest fracture strength was observed for the FRC specimens which exhibited a statistical failure demonstrated by a region of plastic deformation which was related to damage accumulation in the form of rupture of the fibres located in the tensile side of the specimens (Figure 2.3B), followed by a region of unstable condition [23]. This behaviour was observed as deviation from linearity observed on the load-displacement diagram (Figure 2.2A). For the bilayer specimen, two patterns of different behaviour were observed; (i) when the fibres where on the compressive side (FRC-c), the specimens failed at a low load comparable to that of specimens made of PFC alone. Additionally, there was a sudden drop in the applied load indicating fracture of the PFC-part, followed by a more or less horizontal component in the load-displacement curve where the remaining fibres carried the applied load (Figure 2.2D and Figure 2.3C). On the other hand, (ii) when the fibres were on the tensile side (FRC-t) the specimens failed at a significantly higher load and demonstrated behaviour more
comparable to FRC specimens (Table 2.2 and Figure 2.2B). Nevertheless, all specimens demonstrated also compressive fracture of the PFC (Figure 2.3D).

SEM analysis of FRC-PFC specimens that were subjected to rotational fatigue, demonstrated different fracture behaviour. The first sign of damage accumulation was observed in the PFC which is the weaker component in these specimens (Figure 2.4A). The crack propagated from this region (Figure 2.4B) towards the interface between PFC and FRC (Figure 2.4C) resulting in debonding between the two layers. Afterwards the remaining fibres sustained the applied load until reaching their rupture strength (Figure 2.4D) leaving signs of brittle fracture on every single fibre.

**Figure 2.2** Load-displacement diagrams of the tested groups: PFC demonstrated elastic behaviour and sudden catastrophic failure (graph C). FRC demonstrated the highest fracture strength (graph A). FRC in compression (graph D) demonstrated initial sudden drop in load as soon as the PFC layer was broken. The highest toughness as associated when FRC was in tension (graph B) as demonstrated by the zigzag plateau following the highest point on the graph.
Figure 2.3 Scanning electron micrographs (SEM) of specimens subjected to a cantilever beam test: (A) SEM image, 65x, of a PFC specimen. Defect origin is demarcated with white arrow. Observe the compression curl on the opposite side. (B) SEM image, 61x, of a FRC specimen. Observe damage accumulation on the tensile surface meanwhile the compressive side remains intact. (C) SEM image, 50x, demonstrating deflection of the crack at the FRC-PFC interface of a FRC-compression specimen. (D) SEM image, 50x, of a FRC-tension specimen, demonstrating a compression crack.
**Figure 2.4** Scanning electron micrographs (SEM) of specimens subjected to a rotating cantilever beam fatigue test: (A) SEM image, 100x, of a bilayer specimen. Observe damage accumulation at the periphery of the specimen (black arrow) and defect origin (white arrow). (B) SEM image, 500x, detailed view of the defect origin of a bilayer specimen. (C) SEM image, 672x, demonstrating debonding at the FRC-PFC interface (white arrows) of a bilayer specimen. (D) SEM image, 3000x, demonstrating signs of brittle fracture on an independent fiber. Observe debonding between the fiber and the resin matrix.
2.5 Discussion

The resin-based composites used in this study are composed, on a structural level, of a mixture of different heterogeneous materials, which influences their mechanical properties. PFC on one hand is basically composed of brittle inorganic reinforcing filler particles with a high elastic modulus which are embedded in a quasi-brittle organic resin matrix. Nevertheless, it could be considered as single phase material with regard to measuring its mechanical properties as fracture strength, fatigue resistance, or work-of-fracture. On the other hand, the macroscopic size of the unidirectional fibre bundles used in FRC could influence its mechanical performance. This may offer a direct obstacle in the path of crack growth which requires paying careful attention to analyzing the behaviour of this material in order to obtain justified mechanical properties values. Finally, the bilayer of FRC and PFC should be considered as a two phase structure with consideration that the interface between these two different structures could also influence the performance of the specimens [24].

The rotational fatigue testing method applies a multi-vectorial stress on the specimens to be tested in a sequence of one tension and one compression per cycle. In fact, the direction of the applied stress represents the clinical situation where stresses on occlusal surfaces vary from parallel to the surface to perpendicular. The used test methodology subjects each point of the circumference of a specimen to tensile stress, implying calibration onto the weakest location [25]. According to Baran et al. [20] the staircase method virtually implies a fatigue limit and therefore not appropriate for lifetime predictions. It must be realized that the obtained test results do not represent the clinical fatigue life, but the method itself clearly indicates differences between and among the materials tested. The goal of the current investigation was rather to evaluate the differences in fatigue between the materials, than to predict the clinical fatigue. If this method not only reveals the mutual differences, but also predicts clinical behaviour, the question to be answered is which number of cycles represents the clinical situation. In the dental literature the opinions about the number of test cycles to be used, vary widely from $10^3$ to $10^6$ [26]. No hard evidence exists concerning the number of chewing strokes annually. Estimations have been made on these numbers per year and they vary considerably: Wiskott et al. [27] estimated $10^6$ cycles annually. Huysmans et al. [28] concluded that composite restorations either fail before $10^4$ cycles or after $10^5$ cycles. Braem et al. [29] concluded that in vitro fatigue testing is not conclusive. Research into the relationship between stress and cycle numbers (S-N curves) [30] of unidirectional glass/epoxy composites revealed that low-cycle fatigue
Fatigue of resin composites

(0.25 Hz) with high loads leads to failure in less than $10^4$ cycles, supporting our choice of number of cycles. Furthermore, they observed a lower survival rate for low-cycle fatigue compared to high-cycle fatigue (5 – 10 Hz). The choice for the rotation frequency of 1.2 Hz has been made on a clinical basis, assuming that the upper limit of the chewing frequency is two strokes per second [29].

The outcome of fatigue experiments can be a relationship between stress and number of cycles, \textit{i.e.} the S-N curve (endurance curve or Wöhler curve), or a fatigue resistance at a predetermined number of cycles. In comparison to the determination of the fatigue resistance the generation of a S-N curve involves a tedious and time consuming procedure. Determination of fatigue resistance at a predetermined number of cycles by the staircase method requires fewer tests ($n = 15 - 20$) and concentrates testing automatically near the mean.

Fiber-reinforcement significantly increased the fracture strength of resin-based composites. Flexural strength data found in the literature for Filtek Z100 range from 123 MPa to 151 MPa and are slightly lower than the 164.9 MPa found in this study [31,32]. Various factors might explain the slightly higher values found in our study. The experimental set-up might had influence on the results, so for that reason it should be noted that values from the literature were obtained by three-point bending tests instead of a cantilever beam test. Also the cross-sectional design and the L/D ratio (length/diameter) [33] of the specimens and the cross-sectional design, \textit{e.g.} circular versus rectangular, can influence the obtained values. Flexural strength data for everStick obtained in this study (936.1 MPa) are comparable with the data found in literature (559 MPa till 1164 MPa) [34,35]. Only one study reports on the fracture strength of resin-based composites obtained by a cantilever beam test [36]. Although the exact values of both studies are incomparable, due to differences in specimen dimensions, fibre distribution and volume, a significant increase in fracture strength for FRC was noted in both studies [36]. When FRC was placed in compression, the fracture strength of the bilayer specimens was lower, but not significant different from homogeneous beams made of PFC resin. On the other hand, when the FRC was placed in tension, the strength was significantly increased, but still considerably below the fracture strength of homogeneous FRC beams (Table 2.2).

Few data are available on rotational fatigue resistance of dental resin-based composites. Only one study reports on the rotational fatigue resistance of PFC [37]. Scherrer \textit{et al.} [37] studied the rotational fatigue resistance of PFC for provisional and definitive restorations and report a rotational fatigue resistance for the latter group (Artglass, Targis and Colombus) between 54.6 MPa and 62.1 MPa, which is
comparable with the observed value of Filtek Z100 (51.5 MPa). When comparing the rotational fatigue resistance values to flexural strength values they observed a ratio between 38 and 62% which is higher than our value of 32%. A possible explanation is the difference in test set-up between fracture strength and fatigue resistance (3-point bending vs. cantilever beam), which is not the case in our study. Braem et al. [38] and Gladys et al. [39] reported only a difference of 30% between flexural strength and fatigue resistance of Filtek Z100. Although, it should be noted that they used a restrained 3-point bending set-up for the determination of fracture strength and fatigue resistance.

No literature is available on the rotational fatigue resistance of FRC. Nevertheless, the fatigue resistance of FRC is investigated in a multitude of studies [17-19,40,41]. Bae et al. [41] studied the dynamic fatigue strength of bar-shaped specimens made of a combination of FRC and PFC and tested in a three-point bending mode according the staircase method. Their fatigue strength values ranged from 90.2 MPa (Targis Dentine/Vectris Frame) and 196.9 MPa (Sculpture Body/FibreKor). In comparison our value of 116.5MPa obtained with specimens made of PFC and FRC is relatively low, which is obvious when taking the multi-vectorial nature of our test set-up into account. In the three-point bending test used by Bae et al. [41] FRC is subjected to tensile stresses and PFC to compressive stresses, while the rotating cantilever fatigue test subjects PFC as well as FRC to both types of stresses. Such a multi-vectorial stress application implies that the weakest material (PFC subjected to tensile stress) will cause failure. Although the incompatibility of the data we can conclude from the literature and also from our study that FRC are more fatigue resistant than PFC [20].

Work-of-fracture is the amount of energy needed to fracture a specimen and is a measure of toughness. It was clearly shown that specimens made of FRC (0.55 kJ·m⁻³) exhibit a higher work-of-fracture than specimens made of PFC (27.90 kJ·m⁻³) only. These results were in accordance with previous studies [42,43]. Petersen et al. showed that incorporation of glass fibres increased work-of-fracture [43] and showed the correlation between fibre volume fraction and work-of-fracture [42]. Specimens made of a combination of FRC and PFC, containing only half the amount of FRC and PFC, showed values in-between those of FRC and PFC.

Failure mode analysis of the broken specimens enabled better understanding of the failure mechanism of the different tested specimens. It is well known that the presence of fibres affects the fracture process which results in interrupting crack growth progression and thus enhances the fracture toughness of the FRC material.
Structural flaws are always present in the resin matrix and under the influence of cyclic loading micro cracks start to develop as the initial sign of failure. With continuous loading and due to the effect of stress concentration at these structural defects, micro cracks start to grow and join each other to form larger cracks serving as an entrance for oral fluids and bacteria, which may further accelerates the failure process. The presence of fibres ahead of and behind the crack tip significantly influences this process [24]. The presence of different components in one beam presented different physical barriers (including the influence of interface and bond strength between FRC and PFC resins) in the direction of crack propagation which resulted in preventing immediate failure and prolonged the failure process. This behaviour could be extremely beneficial in clinical conditions were fatigue is the most influential failure mechanism. Nevertheless, the restoration should be designed to bring the supporting fibres in tension in order to gain any strength benefit.

2.6 Conclusion

Although both cantilever beam test and rotating cantilever beam fatigue test are well established in the field of engineering, they are only introduced recently into the field of dentistry for the evaluation of resin-based composites. Within the limitations of this study, the following conclusions can be drawn: (i) the fatigue resistance of resin-based composites is lower than their fracture strength, (ii) FRC exhibits higher fracture strength and work-of-fracture than PFC, (iii) FRC are more fatigue resistant than PFC or combinations of FRC and PFC and, (iv) paying attention to the behaviour of fibre-reinforced composites is a key parameter to insure long term performance and adequate fatigue resistance.
2.7 References


