Layer structure and load-bearing properties of fibre reinforced composite beam used in cantilever fixed dental prostheses

Pasi ALANDER1,2, Leila PEREA-LOWERY3, Kalevi VESTERINEN3, Auli SUOMINEN4, Eija SÄILYNOJA2,5 and Pekka Kalevi VALLITTU2,6

1 Degree Programme in Dental Technology, Faculty of Health and Well-being, Turku University of Applied Science, Turku, Finland
2 Department of Biomaterials Science, Institute of Dentistry, University of Turku, Turku, Finland
3 Technology Industry, Faculty of Engineering and Business, Turku University of Applied Sciences, Turku, Finland
4 Department of Community Dentistry, Institute of Dentistry, University of Turku, Turku, Finland
5 Scientific Affairs and Administration, Stick Tech Ltd. —a member of GC Group, Turku, Finland
6 City of Turku, Welfare Division, Turku, Finland

Corresponding author, Pasi ALANDER; E-mail: pasi.alander@turkuamk.fi

This study evaluates the effect of fiber reinforcement quantity and position on fracture load of fixed dental prostheses specimens with different fibre reinforced composite (FRC)/particulate filler composite (PFC) ratio in a cantilever beam test. Three types of specimen structures were made: Specimens with FRC, PFC, or with a combination of both. Specimen’s size was 2.0×2.0×25 mm³ and the thicknesses of the FRC layers were 0, 0.5, 1.0, 1.5 and 2.0 mm. The layers of FRC were placed at the top or at the bottom. Eight groups of specimens were evaluated (n=15/group). The test specimens were statically-loaded until fracture. The fracture loads were linearly dependent on the quantity of the FRC reinforcement when placed at the top (R²=0.941) and bottom (R²=0.896) of the specimens. ANOVA revealed that reinforcement position on the tension side and higher FRC reinforcement volume in the test specimens had positive effect to load bearing capacity (p<0.001).

Keywords: Fiber-reinforced composite, Cantilever testing, Fracture strength, Fiber position, Fiber quantity, Fixed dental prostheses

INTRODUCTION

The number of indications for using resin-based particulate filler composite (PFC), has increased on account of their improved physical and mechanical properties. Nowadays, resin-based PFCs are indicated for direct and indirect restorations in the anterior and posterior zones of the oral cavity. Fixed dental prostheses (FDP) must be designed to resist the same magnitude of forces as intact natural teeth. In clinical situations, FDPs should resist masticatory forces, which equivalent to 150 N in the anterior area8 and in the range of 500 N to 900 N posteriorly2-9. Fiber-reinforced composites (FRC) represent an advisable treatment alternative for FDPs by virtue of their advantageous mechanical properties, suitable flexural strength and favorable esthetics4-6.

In order to withstand chewing forces, resin-based FDPs are strengthened with the addition of FRC reinforcement. In these types of restorations, the FRC framework distributes the stress, maintaining the integrity and increasing the longevity of the prosthetic device10. The mechanical properties of FRC restorations range from isotropic to anisotropic and are greatly influenced by the type, volume, location and direction of the fibers5,9. Long continuous fibers have shown outstanding performance on the reinforcement of PFC when located at the tensile side of restorative appliances10. The thickness of the material, the design of the preparation, as well as the properties of the luting agent are factors that have a direct influence on the strength of fiber-reinforced composite fixed dental prostheses (FRC FDPs)11.

A material with high flexural strength, high elastic modulus and low deformation is required in high stress bearing areas. The fracture resistance of the restorative material is then evaluated and used as a predictor of the clinical performance of the prosthetic device12. Some investigations have reported the flexural strength of FRC reinforcement beams following the international standards for performing three-point bending test13-16. In this type of test, a specimen rests on two supports at both ends and it is centrally loaded using a loading tip. This test set-up replicates a clinical situation where the FPD is cemented on both ends (fixed-fixed design). It has been reported that in the fixed-fixed FDP designs, the FRC reinforcement should be placed in the region where the highest tensile stresses are likely to occur. In the pontic area this takes place near the alveolar ridge6,17. In cantilever FDP situations the three-point bending test results can be partly questioned and the cantilever two-point test set up would give more realistic values, because of the stress distribution in the bridge is related to bridge design (cantilever or fixed-fixed)18.

Some reports on the clinical success of FDPs demonstrate that although tooth preparation, patient selection and framework design are important factors19-22, the number of abutments connected to the pontic seems to also be a key component23. Some investigations have found association between rigidly splinted abutments and debonding rates24,25, where for every fixed splinted abutment, the likelihood for debonding increased. Contrarily, 2-unit cantilevered
FDPs showed good and sometimes even better clinical retention than 3-unit fixed-fixed FDPs.26 This is due to the freestanding disposition of the single abutment, which defeats the adverse interabutment stresses associated with fixed-fixed designs. A number of clinical studies indicate the reliability of 2-unit cantilever FDPs.

In cantilever design FRC FDPs, the FRC positioning within the prosthetic device plays an important role in the clinical outcomes and longevity of the restoration. However, differences in the ratio of FRC/PFC are not clearly defined for creating clinical parameters when constructing cantilever FRC FDPs. Accordingly, the aim of this study was to evaluate in vitro the influence of FRC on the load-bearing capacity of PFC by means of a cantilever beam test by varying the internal composite layer structure of PFC and FRC in the test specimen. The null hypotheses to be tested was as follows: (i) placing the FRC reinforcement in the tension side, and (ii) increasing the FRC reinforcement amount in the FDPs improves their load-bearing capacity in cantilever beam test.

MATERIALS AND METHODS

A PFC and FRC reinforcement were selected for this investigation. The commercial brands and composition of the materials used are summarized in Table 1. One hundred and twenty rectangular bar-shaped specimens (2×2×25 mm³) were made of PFC and FRC reinforcement. The materials were placed into a stainless-steel split mold and pre-polymerized with a hand-held LED curing unit for 60 s on its top and bottom surfaces (The Cure TC-01, Spring Health Products, Norristown, PA, USA) with a power output of 1,000 mW/cm² (The Cure TC-01, Spring Health Products, Norristown, PA, USA) on the bottom and with plastic foil (Transparent foil, Ivoclar, Schaan, Liechtenstein) on the top. To avoid any air bubbles in the test specimens, the mold was pressed between the two glass plates. The light tip of the led curing unit was placed 2 mm away from the test specimen's surface. Five minutes were used for a final polymerization, which was carried out in a light curing device (Labolight LV-III, GC, Tokyo, Japan). The test specimens were stored in dry conditions for 30 days at room temperature (22±1°C) before the testing was performed.

Eight groups of 15 specimens each were made. Control groups were made solely from FRC reinforcement and PFC. The rest of the groups were made using a combination of both materials. The height of the FRC reinforcement portion in the specimen’s cross-section was 0, 0.5, 1.0, 1.5 and 2.0 mm, corresponding to a 0, 25, 50, 75 and 100% volume percentage (vol%) respectively. The FRC prepregs used were made of continuous unidirectional fibers containing 2000 (everStickPERIO) or 4000 (everStickC&B) single E-glass fibers and dimethacrylate resin matrix. The FRC reinforcements were placed either at the tension side of the specimens (top), or on the compression side of them (bottom) (Table 2).

The fracture loads (in N) were obtained by subjecting the specimens to a cantilever beam test. The test specimens were clamped at one end (Fig. 1) and the span between the support and the loading tip was 10 mm. The load was applied with a universal loading machine (Lloyd LRX, Lloyd instruments, Fareham, England) at a crosshead speed of 1.0 mm/min using a steel loading tip. The limits for the test were a deflection of 8 mm or a decrease of 20% of the load. The load was recorded using the Lloyd Nexxygen program (Lloyd Instruments). The load-bearing capacities were determined using the applied load (N) at the highest point of the load-deflection curve.

The flexural strength (MPa) was calculated from load values (N) using the following formula:

\[ \sigma_{\text{max}} = \frac{F b l}{6 h^2} \]

\( \sigma_{\text{max}} \) corresponds to the flexural strength in megapascals, \( F \) is the maximum load in newtons, \( l \) is the distance from the support to the concentrate loading point (10.0 mm), \( h \) is the height (2.0 mm) of the specimens, and \( b \) is the width (2.0 mm) of the specimen.

For calculating the cross-sectional dimensions of the cantilever beam, which withstands the simulated occlusal loads of 150 N, 500 N and 900 N before failure, the following formula was used, where \( d \) represents the length of the side of the square in millimeters.

| Table 1 Commercial materials used in the fabrication of the specimen |
|------------------|------------------|------------------|
| Brand            | Manufacturer       | Lot no.          |
| everStickC&B     | GC Europe, Leuven, Belgium | 240020140331     |
| everStickPERIO   | GC Europe          | 120020140428     |
| G-aenial Universal Flo A3 | GC, Tokyo, Japan   | 140114B        |

1 E-glass fiber prepreg impregnated with light polymerizable semi-interpenetrating polymer network PMMA-BisGMA resin matrix. Fiber/matrix content in both FRC reinforcement products were around 65/35 and everStickPERIO contains 2000 and everStickC&B contains 4000 single E-glass fibers (based on the manufacturer's information).

2 UDMA/ethylene dimethacrylate particulate filler composite resin.
Table 2 Description of the test groups investigated and their FRC reinforcement quantity

| FRC quantity in mm and vol% | FRC products | FRC position | Code       |
|----------------------------|--------------|--------------|------------|
| 0 mm (0%)                  | —            | top          | 0 mm       |
| 0.5 mm (25%)               | everStickPERIO (2000 single fibers) | top | 0.5 mm (top) |
|                            |              | bottom       | 0.5 mm (bottom) |
| 1.0 mm (50%)               | everStickC&B (4000 single fibers) | top | 1.0 mm (top) |
|                            |              | bottom       | 1.0 mm (bottom) |
| 1.5 mm (75%)               | everStickC&B+PERIO (6000 single fibers) | top | 1.5 mm (top) |
|                            |              | bottom       | 1.5 mm (bottom) |
| 2.0 mm (100%)              | 2× everStickC&B (8000 single fibers) | top and bottom | 2.0 mm |

Fig. 1 Cantilever test set-up with concentrate loaded at the 10 mm point. The radius for the curvature of the supporting point was 5 mm.

\[ d = \sqrt[3]{\frac{F \times (l \times 6)}{\sigma_{\text{max}}}} \]

Correspondingly, the maximum beam length was calculated for the specimens to withstand simulated occlusal loads of 150 N, 500 N and 900 N using the following formula:\[ l = \frac{\sigma_{\text{max}} \times d^3}{F \times 6} \]

Failure mode analysis
Microscopic photographs of the specimens after testing were taken to evaluate the fracture type and FRC reinforcement quantity. This was made using a light microscope (wild M32 Kombistereo, Heerbrugg, Switzerland) with a 2×magnification. Additional analysis of the fracture types was made using a stereomicroscope (Fino Stereomicroscope M-86001, Fino, Bad Bocklet, Germany) with 10×magnification. The fracture types were classified as follows:

1. Fracture of the FRC reinforcement
2. Fracture of the PFC
3. Fracture of both, the FRC reinforcement and PFC
4. A combination of fracture and delamination.

Statistical analysis
Means and standard deviations (SD) were calculated for fracture load for each FRC reinforcement in terms of quantity and position. Statistically significant differences were evaluated using two-way analysis of variance (ANOVA). The independent factors were FRC reinforcement quantity and position, and their interaction. The dependent variable was fracture load. The frequencies for fracture types between FRC reinforcement quantity and position were examined and were reported as percentages with Fisher’s exact test. The level for statistical significance was considered at \( p < 0.05 \). All analyses were conducted using SAS statistical software (SAS Institute Inc., Cary, NC, USA) to compare the load required to cause fracture or delamination of the specimens. The assumption of normality was assessed visually by the figures.

RESULTS
A representation of the load-deflection curves of the different groups investigated can be seen in Fig. 2. Load-deflection curves in the groups 0 mm, 0.5 mm bottom and 1.0 mm bottom are described as instantaneous failure. Curves in the groups 1.5 mm top, 1 mm top and 0.5 mm top are described as statistical failure (series of small intense fractures which are prevented from becoming catastrophic). Curves from the groups 2 mm and 1.5 mm bottom are described as bending type stepwise failures. The load required to cause fracture or delamination varied from 12 N to 64 N, with the highest being found on the full FRC group (2 mm) (Fig. 3). The lowest fracture load was seen in the group without FRC reinforcement (0 mm). All groups where the FRC reinforcements were placed at the top surface of the specimens (tension side) withstood higher forces than their counterparts, which had FRC reinforcement placed at the bottom (compression...
When compared with the groups with similar FRC reinforcement quantity at the top or at the bottom of the specimens, a bigger fracture load drop by percentage was seen with the groups with low FRC reinforcement quantity. The fracture load drop by percentage was: 57% (0.5 mm), 50% (1 mm) and 23% (1.5 mm). Statistically significant differences were found between FRC positioning when the quantity of FRC reinforcement was low (0.5 mm or 1 mm) ($p<0.001$). Both, the FRC reinforcement quantity and the FRC position affected the fracture load values ($p<0.001$). Fracture load values were linearly dependent on the FRC reinforcement quantity when placed at the top ($R^2=0.9416$) and at the bottom ($R^2=0.896$) of the specimens (Fig. 3).

Tables 3 and 4 summarize the examples of calculated cross-sectional dimensions and maximum span lengths of specimens by which simulated occlusal loads of 150 N, 500 N and 900 N can be withstood before fracturing.

Fracture type percentages are shown in Fig. 4. Photomicrographs of test specimens after the loading test are shown in Fig. 5. The Fisher’s exact test revealed that both, FRC reinforcement positioning and quantity significantly influenced the fracture types ($p<0.001$). No fracture in composite was seen when the FRC reinforcement was at the top of the specimen. A fracture of the FRC was predominantly seen when the FRC
Table 3 Examples of calculated cross-sectional dimensions of beams which provide load bearing capacity before fracture for simulated occlusal loads of 150, 500 and 900 N

| Groups       | 150 N         | 500 N         | 900 N         |
|--------------|---------------|---------------|---------------|
| 0 mm (0 %)   | 4.6 mm×4.6 mm | 6.9 mm×6.9 mm | 8.4 mm×8.4 mm |
| 0.5 mm (top) | 3.2 mm×3.2 mm | 4.8 mm×4.8 mm | 5.8 mm×5.8 mm |
| 0.5 mm (bottom) | 4.3 mm×4.3 mm | 6.3 mm×6.3 mm | 7.7 mm×7.7 mm |
| 1.0 mm (top) | 3.1 mm×3.1 mm | 4.6 mm×4.6 mm | 5.6 mm×5.6 mm |
| 1.0 mm (bottom) | 3.9 mm×3.9 mm | 5.8 mm×5.8 mm | 7.1 mm×7.1 mm |
| 1.5 mm (top) | 2.8 mm×2.8 mm | 4.1 mm×4.1 mm | 5.0 mm×5.0 mm |
| 1.5 mm (bottom) | 3.0 mm×3.0 mm | 4.5 mm×4.5 mm | 5.5 mm×5.5 mm |
| 2.0 mm (100 %) | 2.7 mm×2.7 mm | 4.0 mm×4.0 mm | 4.8 mm×4.8 mm |

Table 4 Examples of calculated beam lengths of beams which provide load bearing capacity before fracture for simulated occlusal loads of 150, 500 and 900 N

| Groups       | 150 N         | 500 N         | 900 N         |
|--------------|---------------|---------------|---------------|
| 0 mm (0 %)   | 0.83 mm       | 0.25 mm       | 0.14 mm       |
| 0.5 mm (top) | 2.4 mm        | 0.73 mm       | 0.41 mm       |
| 0.5 mm (bottom) | 1.0 mm       | 0.31 mm       | 0.17 mm       |
| 1.0 mm (top) | 2.8 mm        | 0.85 mm       | 0.47 mm       |
| 1.0 mm (bottom) | 1.4 mm       | 0.42 mm       | 0.23 mm       |
| 1.5 mm (top) | 3.8 mm        | 1.1 mm        | 0.64 mm       |
| 1.5 mm (bottom) | 2.9 mm       | 0.87 mm       | 0.48 mm       |
| 2.0 mm (100 %) | 4.2 mm        | 1.27 mm       | 0.71 mm       |

Fig. 4 Schematic drawing of the specimen and distribution (%) of fracture types in relation to the position of FRC reinforcement.

reinforcements were located at the top of the specimens with 73% average value of 0.5, 1.0 and 1.5 mm top groups.

The opposite situation was seen in the groups where the FRC was positioned within the compression side (bottom). In those groups no fractures in FRC reinforcement alone were identified. When the FRC was positioned within the compression side, the typical
fracture types were: Combination of fracture and delamination (0.5 mm from bottom), fracture in the PFC (1 mm from bottom) and the fracture of both, FRC reinforcement and PFC (1.5 mm from bottom).

DISCUSSION
Fiber-reinforced composite FDPs face different mechanical loads. Since they are subjected to the same kinds of forces as natural teeth, their design must incorporate the mechanical aspects needed to resist those forces\textsuperscript{31}. This experimental study was designed to investigate the load-bearing capacities of FRC structures simulating cantilever restorations where a variety of FRC reinforcement was used. The effect that quantity and positioning of fibers had on the load-bearing capacities of these kinds of restorations was also evaluated. The null hypotheses were accepted, FRC reinforcement on the tension side (top) and higher FRC reinforcement volume in test specimens had a positive effect on load bearing capacity in cantilever beam test.

It should be noted that the calculations made in this study for cross-sectional dimensions of beams have some limitations. The formulas used in this study are made to characterize linear isotropic properties of a material. Typically, dental composites or cast metal have linear isotropic properties up to the yield point during the bending. After the yield point, these materials behave nonlinearly as can be seen from the test specimens in the load-deflection curves (Fig. 2). With FRC reinforcement as tested in this study, the maximum load (N) is reached at a higher load level than the yield point. Despite this, simplified formulas may be used to obtain estimations of how large the cross-section needs to be, or how short the span in cantilever FRC FDPs should be to withstand the biting forces in the anterior (150 N) and posterior zones (500 N to 900 N).

A variety of factors have an influence on the physical properties of dental FRCs, some of them are: tensile strength and elongation of fiber and polymer matrix, surface treatment and type of fibers, orientation and length of fibers, number and diameter of fibers as well as location of the FRC in the dental reconstruction\textsuperscript{32,33}. The mechanical properties of an FRC framework can be altered by changing the orientation of fibers, their content and geometry, which is known as cross-sectional
design. In the present study, the content of FRC had a significant influence on the load-bearing capacities of the FRC structures investigated. The more FRC was used, the higher the load-bearing capacity became. Fully fiber-reinforced specimens (100% by volumetric portion of FRC reinforcement) were five times stronger than the non-reinforced specimens.

A clinical study demonstrated that distal cantilever units in cross-arch bridges with unilateral posterior two-unit cantilevers are exposed to relatively small biting forces. This was made in comparison with the local forces in the contralateral posterior end abutment region and the forces in the anterior regions. The maximal biting forces in habitual occlusion for cantilever units observed in that study were of 37 N. The periodontal tissue support might explain the smaller chewing forces and lesser degree of muscular utilization during chewing. In the present study, the load-bearing capacities achieved were in the range of 12 N to 64 N (Fig. 3), the highest being found in the group with the highest quantity of FRC. On the contrary, the lowest values were found in the specimens with no FRC. Nevertheless, the fracture mechanism of restorations is based on dynamic loading rather than static loading, and therefore fatigue strength could represent an even more important role than load-bearing capacity.

When designing FRC restorations it is crucial to take into consideration the available vertical space and size of the connectors. Continuous unidirectional fibers should have a cross-sectional design at the connector's site with the aim of providing good resistance against occlusal forces. Thickness and width of the connectors are crucial parameters when stiffness and strength are optimized, which is required to obtain long-lasting restorations. The occlusal distance between an abutment and the antagonist tooth surface should be 2 mm at minimum, 4 mm for the connector area, and 2 mm for the occlusal thickness of the pontic. The cross-section of a connector should have the maximum amount of fibers in volume. However, in cases with surplus space, the highest strength is provided by placing the fibers on the tension side of the connectors in addition to allocating the veneering PFC in the remaining space.

When approximating cross-sectional dimensions and beam length for clinically relevant load-bearing capacities, we selected simulated occlusal loads of 150, 500 and 900 N representing the borderline values within the loads that could be presented clinically. A load value of 500 N could be relevant in the premolar region of dental arches and the approximation calculation showed that fully FRC beams should have dimensions of 4.0×4.0 mm for withstanding the load. Clinically, these FDP connector dimensions could hardly be used, whereas FRC beams, which withstand a 150 N load can easily have clinical applicability. Differently, when the beam length is used to ensure high enough load-bearing capacity, it was found that beam length can be 4.2 mm for achieving load bearing capacity with full FRC beams, which were in this study group 2.0 mm having 2 pieces of everStickC&B FRC reinforcements (total 4000 single fibers). This beam length is approximately the mesio-buccal width of a premolar. Obviously, these approximations are valid only for strength of the beams and attachment of the cantilever beam structure to the abutment was not taken into account.

Previous reports have shown that positioning the framework at the site of the tensile stress, in addition to orienting the fibers along the direction of the stress increases the stiffness and fracture strength of a dental prosthesis. A FRC design should include the fibers oriented in the same direction as the maximum principal stress, which enhances the fracture strength of the FDP and avoids fractures. In the current study, the position of the fibers affected significantly the three investigated parameters, the load-bearing capacity, deflection and fracture type of the tested specimens. The recommended position of fibers in a cantilever restoration is on the tension side, which is near the occlusal surface. A decreased load-bearing capacity was also found in the present study when the fibers were within the compression side.

In terms of the positioning of fibers, it was also found that even when using the same amount of fibers but placed in different locations, the load-bearing capacities varied. That might suggest that in clinical cases where a limited occlusal space is available for adding a high volume of fibers, placing them in the correct position might guarantee a successful outcome. Further investigations are needed to assess the clinical behavior of cantilever FRC FDPs that follow the parameters found as advantageous in this study.

CONCLUSION

This study shows the importance of the FRC reinforcement positioning in cantilever indications. The results suggested that FRC reinforcement should be within the tension side which is near the occlusal surface of the cantilever bridge. When low quantity of FRC reinforcement is used to reinforce the cantilever FDP, the correct FRC positioning is more important than in the situations where lot of FRC reinforcement can be used.

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CONFLICTS OF INTERESTS

Author PA works a freelance trainer for Stick Tech —Member of GC Group. Author ES works in the Research Development and Production Department at Stick Tech Ltd. —Member of GC Group. Author PV
consults for Stick Tech —GC in R&D and education.

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