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The influence of framework design on the load-bearing capacity of laboratory-made inlay-retained fibre-reinforced composite fixed dental prostheses

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ABSTRACT

Delamination of the veneering composite is frequently encountered with fibre-reinforced composite (FRC) fixed dental prosthesis (FDPs). The aim of this study is to evaluate the influence of framework design on the load-bearing capacity of laboratory-made three-unit inlay-retained FRC-FDPs. Inlay-retained FRC-FDPs replacing a lower first molar were constructed. Seven framework designs were evaluated: PFC, made of particulate filler composite (PFC) without fibre-reinforcement; FRC1, one bundle of unidirectional FRC; FRC2, two bundles of unidirectional FRC; FRC3, two bundles of unidirectional FRC covered by two pieces of short unidirectional FRC placed perpendicular to the main framework; SFRC1, two bundles of unidirectional FRC covered by new experimental short random-orientated FRC (S-FRC) and veneered with 1.5 mm of PFC; SFRC2, completely made of S-FRC; SFRC3, two bundles of unidirectional FRC covered by S-FRC. Load-bearing capacity was determined for two loading conditions ($n = 6$): central fossa loading and buccal cusp loading. FRC-FDPs with a modified framework design made of unidirectional FRC and S-FRC exhibited a significant higher load-bearing capacity ($p < 0.05$) (927 ± 74 N) than FRC-FDPs with a conventional framework design (609 ± 119 N) and PFC-FDPs (702 ± 86 N). Central fossa loading allowed significant higher load-bearing capacities than buccal cusp loading. This study revealed that all S-FRC frameworks exhibited comparable or higher load-bearing capacity in comparison to an already established improved framework design. So S-FRC seems to be a viable material for improving the framework of FRC-FDPs. Highest load-bearing capacity was observed with FRC frameworks made of a combination of unidirectional FRC and S-FRC.

1. Introduction

A fixed dental prosthesis (FDP) is considered as treatment of choice for replacing missing teeth. Since conventional and implant-retained FDPs are invasive, time-consuming, and expensive the dental profession continues the search for alternatives. One such alternative is a fibre-reinforced composite fixed dental prosthesis (FRC-FDP). FRC-FDPs are basically made of a fibre-reinforced composite framework acting as a stress dissipater and are veneered with particulate filler composite (PFC).

Following the introduction of glass fibre-reinforced composites in the early 1990s (Goldberg and Burstone, 1992), their use increased enormously over the last years (Freilich and Meiers, 2004). Limited information is available on their longevity and clinical behaviour, but the available clinical research showed that FRC-FDPs are able to function acceptably for up to five years (Behr et al., 2003; Freilich et al., 2002; Gohring and Roos, 2005; Vallittu, 2004), with reported five year-survival rates between 73% (Gohring and Roos, 2005) and 93% (Vallittu, 2004).

Regardless of the promising results, typical kinds of failures, like delaminating and chipping of veneering composite, were encountered during clinical function (Behr et al., 2003; Freilich et al., 2002; Gohring and Roos, 2005; Monaco et al., 2003). To overcome these failures, the framework design should be modified to support the veneering composite, and the amount of fibres should be increased to improve the rigidity of the FDP (Freilich et al., 2002). The most frequently used FRC framework consists of a bundle of unidirectional FRC placed in the central part of a FDP (Fig. 1B). It seems that the amount of FRC included in such conventional framework is too little to provide the necessary support and rigidity. A high-volume anatomically shaped FRC framework should be able to deal with these shortcomings.

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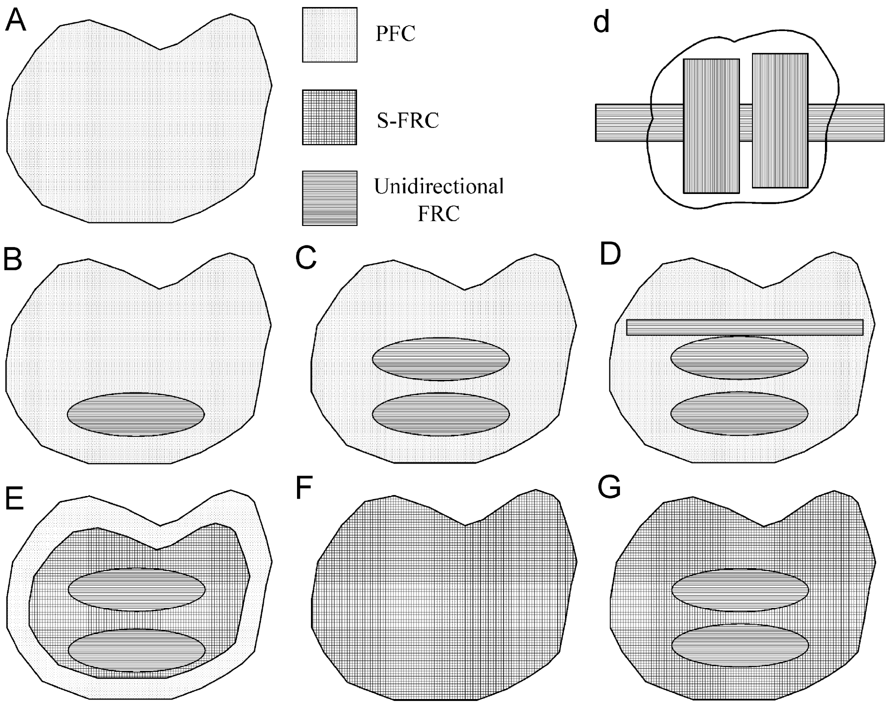

Fig. 1. Graphical representation showing the cross sections of the different framework designs used in this study. (A) PFC: PFC without fibre-reinforcement; (B) FRC1: PFC reinforced with one bundle of unidirectional FRC; (C) FRC2: PFC reinforced with two bundles of unidirectional FRC; (D) FRC3: PFC reinforced with two bundles of unidirectional FRC and two pieces placed perpendicular to the main framework; (d) FRC3: occlusal view; (E) SFRC1: anatomically shaped FRC framework; (F) SRC2: experimental S-FRC; and (G) SRC3: experimental S-FRC and two bundles of unidirectional FRC.

Already some evidence, *in vitro* as well as *in vivo*, is available in the literature on framework design of FRC-FDPs. Behr et al. (2005) tested simulated three-unit FRC-FDPs with one anatomical framework and two conventional framework designs and obtained significant higher fracture resistance for an anatomically shaped framework (902 N) in comparison to conventional frameworks (694 and 737 N). Also Xie et al. (2007) tested the fracture resistance of inlay-retained FRC-FDPs with different framework designs. A framework which supported the pontic area in buccolingual direction showed significant higher fracture resistance compared to conventional and high-volume designs.

Freilich et al. (2002) evaluated the clinical performance of short-span FRC-FDPs and changed during the course of the study, the framework design. The original low-volume framework design, suffered veneer fractures in an early stage. Therefore a high-volume design, which was more rigid and offered more support for the veneering composite, was introduced. The high-volume design showed a 95% survival rate instead 62% for the low-volume design after a mean observation time of 3.75 years. Monaco et al. (2003) investigated the clinical behaviour of inlay-retained FRC-FDPs with conventional and modified framework designs over a period of 12–48 months. The conventional framework design showed a higher failure rate than the modified framework design. In the group of FDPs with a conventional framework design delamination occurred in three cases (16%), while in the modified framework group only one FDP (5%) suffered from chipping.

Short glass-fibres containing fibre-reinforced composite (S-FRC), with semi-interpenetrating polymer network matrix, was recently introduced to dentistry (Garoushi et al., 2007a). Random-orientated S-FRC exhibit isotropic properties in comparison to the anisotropic properties of unidirectional fibres. S-FRC exhibit improved mechanical properties with regard to flexural strength and toughness in comparison to PFC (Garoushi et al., 2007a; Petersen, 2005). Both properties make S-FRC a possible alternative to easily fabricate a high-volume anatomically shaped FRC framework. Garoushi et al. (2007b) showed that short-span FRC-FDPs made of S-FRC exhibited similar load-bearing capacity as conventional FRC-FDPs.

The aim of the present study was to evaluate *in vitro* the influence of framework design on the load-bearing capacity of laboratory-made inlay-retained FRC-FDPs. The null-hypothesis to be tested was that incorporation of S-FRC to FRC frameworks of FRC-FDPs improves their load-bearing capacity and generates a more favourable fracture pattern.

2. Materials and methods

Eighty-four laboratory-made three-unit inlay-retained FRC-FDPs replacing a lower first molar were constructed. The FRC frameworks were made of a commercially available unidirectional E-glass-containing FRC (Everstick C&B, Stick Tech Ltd., Turku, Finland) and a new experimental S-FRC. S-FRC was prepared as described previously (Garoushi et al., 2007a). The FRC frameworks were veneered with hybrid PFC for indirect use (Gradia-dentine A3, GC Corporation, Tokyo, Japan). The materials used in this study and their composition are listed in Table 1.

2.1. FDP preparation

A zirconia model (Ice Zirconia, Zirconzahn, Bruneck, Italy) of a mandibular second premolar, a missing first molar and second molar, prepared to accommodate a three-unit inlay-retained FDP, was created. The inter-abutment distance of 11 mm corresponds with the mesial–distal dimensions of a mandibular first molar. The second premolar received a disto-occlusal inlay preparation (step: 3.0 × 2.0 mm; box: 1.5 × 3.5 mm; depth: 2.0 mm) and the second molar a mesio-occlusal inlay preparation (step: 4.0 × 3.0 mm; box: 1.5 × 5.0 mm; depth: 2.0 mm) according to the guidelines for composite inlay restorations. Preparations were made with conventional diamond burs (set 4278, Komet, Lemgo, Germany) in a water-cooled airrotor.

The FRC-FDPs were fabricated according to seven different framework designs (Fig. 1):

PFC: made of PFC without fibre-reinforcement.
FRC1: made of PFC reinforced with one bundle of unidirectional FRC.

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Table 1
Materials used in this study.

Brand	Composition	Manufacturer	Lot number
Gradia dentine A3	Resin: UDMA, EDMA; filler: silica ($\approx$75 vol%)	GC Corp, Tokyo, Japan	0506021 0608221 0609111
Everstick C&B	Resin: PMMA, Bis-GMA; filler: silanised E-glass fibres ($\approx$65 vol%)	Sticktech Ltd., Turku, Finland	2061010-ES-165
Experimental S-FRC	Resin: Bis-GMA, TEGDMA; filler: silanised E-glass fibres ($\approx$22.5 wt%), silanised silica particles ($\approx$55 wt%)		
Multilink sprint	Base paste: resin: Bis-GMA, TEGDMA, UDMA; fillers: barium glass, ytterbium trifluoride, silica; initiators/stabilizers Catalyst paste: resin: Bis-GMA, TEGDMA, UDMA; methacrylated phosphoric acid ester; fillers: barium glass, ytterbiumtrifluoride, silica; initiators/stabilizers	Ivoclar-Vivadent, Schaan, Liechtenstein	J22739

Bis-GMA bisphenol-A-gycidyl dimethacrylate; UDMA urethane dimethacrylate; EDMA ethylene dimethacrylate; UTMA urethane tetramethacrylate; PMMA poly(methyl methacrylate) Mw 220,000; TEGDMA triethylenglycoldimethacrylate.

FRC2: made of PFC reinforced with two bundles of unidirectional FRC.
FRC3: made of PFC reinforced with two bundles of unidirectional FRC and two pieces placed perpendicular to the main framework.
SFRC1: made of an anatomically shaped FRC framework, composed of two bundles of unidirectional FRC and experimental S-FRC, and veneered with 1.5 mm of particulate filler composite.
SFRC2: made of experimental S-FRC.
SFRC3: made of experimental S-FRC and two bundles of unidirectional FRC.
FRC1 and FRC2 are conventional framework designs, while FRC3, SFRC1, SFRC2, and SFRC3 are modified framework designs.

The FRC framework was light cured for 10 s by a handheld polymerisation unit (Optilux 501, Kerr, CT, USA) with a power output of 800 mW cm^{-2}. The retainer and the molar pontic were veneered with hybrid PFC for indirect use (Gradia, GC Corp.). A transparent polyvinylsiloxane template (Memosil 2, Heraeus-Kulzer, Hanau, Germany) was used to standardise the dimensions and occlusal morphology of each FRC-FDP. Connector dimensions for the premolar were: height 4.0 mm; width 5.0 mm, and for the molar: height 4.5 mm; width 5.5 mm. Each increment was light cured for 20 s by the same handheld polymerisation unit. The completed FDP was post cured by light and heat in a light furnace (Lumamat 100, Ivoclar-Vivadent, Schaan, Liechtenstein) for 25 min. The specimens were dry stored for 24 h prior to luting.

The three-unit FDPs were luted to the zirconia model with a recently introduced self-adhesive, dual-curing resin luting cement (Multilink sprint, Ivoclar-Vivadent, Schaan, Liechtenstein). Pre-treatment of the adhesive surface of the inlay restorations was obtained by sandblasting (Cojet prep, 3 M Espe, St Paul, MN, USA) with 30 μm silica-coated alumina particles (Cojet sand, 3 M Espe) under 0.3 MPa pressure for 10 s, followed by cleaning with compressed air for 5 s. No pre-treatment was required for the zirconia model. Excess luting cement was removed with a microbrush after the FDP was seated. Resin luting cement was light cured from three directions (occlusal, buccal, and lingual) for 40 s by a handheld polymerisation unit. The luted FDPs were left undisturbed for an additional 15 min to allow the resin luting cement to set.

2.2. Load-bearing capacity

Specimens were loaded until failure in a universal testing machine (model LRX, Lloyd instruments Ltd., Fareham, UK) at a crosshead speed of 1 mm min^{-1} and data were recorded using PC software (Nexygen, Lloyd instruments Ltd.). The load was applied by a 6 mm diameter steel contact ball, as previously described (Garoushi et al., 2007b; Xie et al., 2007). Each group of FRC-FDPs was randomly divided into two subgroups ($n = 6$), which were subjected to two different loading conditions: for the first group, the load was applied in the central fossa of the pontic, while for the second group the load was applied to the buccal cusp. The specimens were loaded till initial first signs of damage could be observed. Identification of initial failure was based on criteria described by Dyer et al. (2005): (1) a sharp decline in the load/displacement curve, (2) visible signs of fracture, and (3) audible emissions, if at least two of the following conditions were present, initial failure was identified as such.

Fractured specimens were submerged in a methyl blue dye for 10 min followed by 30 s rinse with tap water. Specimens were visually examined and their mode of failure was recorded. Randomly selected specimen were sectioned (Isomet 1000, Buehler, Lake Bluff, IL, USA) in order to determine the cross-sectional FRC-volume.

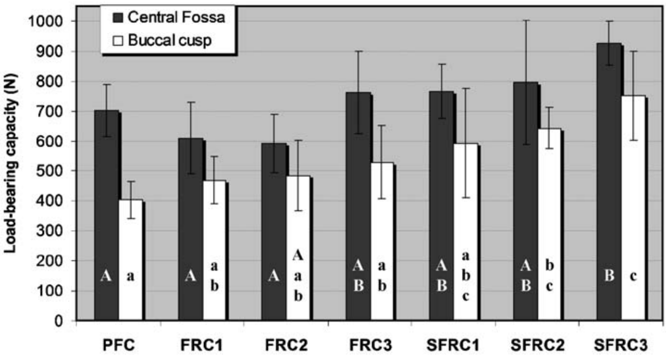

Fig. 2. Load-bearing capacity of FRC-FDPs with different framework designs. Error bars showing the standard deviation. Groups denoted with the same superscript are not statistically different (two-way ANOVA, Tukey multiple comparison, $p < 0.05$).

2.3. Statistical analysis

Statistical analysis was performed with the statistical software SigmaStat 3.0 (SPSS Inc. Chicago, IL, USA). Mean and standard deviations of load-bearing capacities for each group were calculated. Two-way analysis of variance (ANOVA) followed by Tukey's post hoc test was performed to determine the effect of framework design and load condition on the observed load-bearing capacities. p-Values of less than 0.05 were considered to be statistically significant.

3. Results

Load-bearing capacities (in N) of FRC-FDPs with different framework designs are graphically represented in Fig. 2. Significant differences in load-bearing capacity were found between both loading conditions. Central fossa loading produced significant higher load-bearing capacities than buccal cusp loading for all groups ($p < 0.05$), except for FRC2. No strong differences between the different framework designs were revealed. Slightly higher load-bearing capacities were obtained for modified frameworks in comparison to conventional and PFC frameworks. Only SFRC3 (927 ± 74 N) was significant different from PFC (702 ± 86 N), FRC1 (609 ± 119 N), and FRC2 (592 ± 98 N) for central fossa loaded specimens. For buccal cusp loaded specimens, not only SFRC3 (751 ± 148 N) was significant different from PFC (403 ± 62 N), FRC1 (469 ± 80 N), FRC2 (483 ± 117 N), and FRC3 (529 ± 122 N), but also SFRC2 (643 ± 68 N) was significant different from PFC (403 ± 62 N).

Visual inspection revealed three different failure modes: cracks, delamination, and pontic fractures. Modes of failure for the different groups are shown in Table 2. Catastrophic failures were only seen for PFC when loaded at the central fossa. FRC1 and

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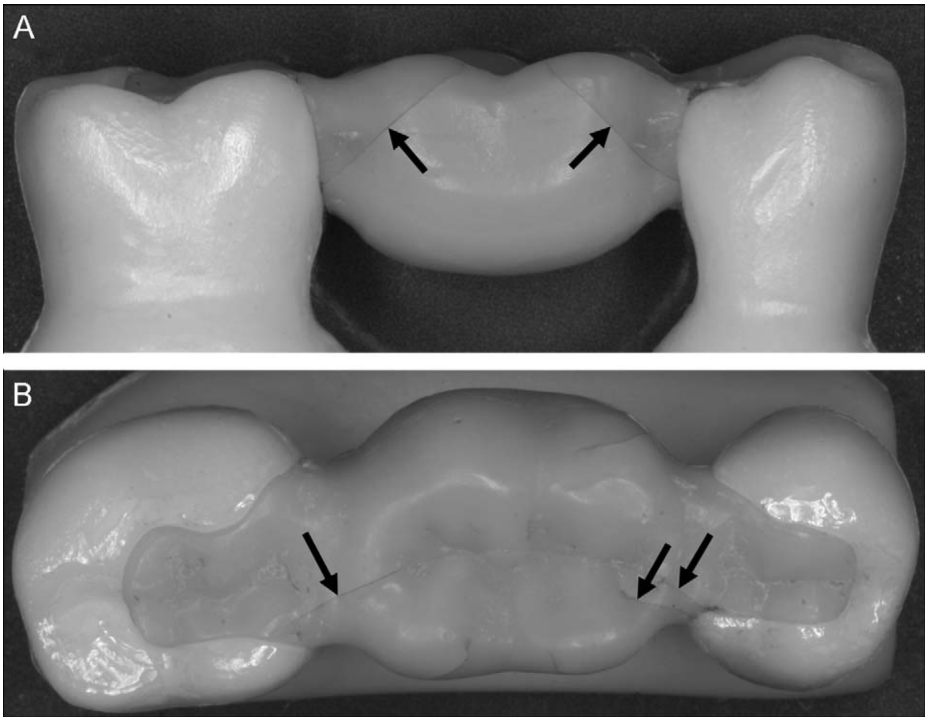

Fig. 3. Failed FRC-FDP (group FRC2) showing cracks (black arrows) originating from the gingival part of the connector towards the loading point.

FRC2 suffered from delamination in up to 50% of the cases. Also one delamination failure occurred in FRC3 when loaded in the central fossa. Cracks were the most common failures and their location was uniform throughout the groups. The cracks originated from the gingival part of the connector toward the loading point (Fig. 3).

Table 2
Fracture patterns of FRC-FDPs with different framework design.

Fracture pattern	PFC		FRC1		FRC2		FRC3		SFRC1		SFRC2		SFRC3	
	CF	BC	CF	BC	CF	BC	CF	BC	CF	BC	CF	BC	CF	BC
Cracks	0	6	3	5	3	4	5	6	6	6	6	6	6	6
Delamination	0	0	3	1	3	2	1	0	0	0	0	0	0	0
Pontic fracture	6	0	0	0	0	0	0	0	0	0	0	0	0	0

4. Discussion

Dental reconstructions are during clinical function subjected to biting and chewing forces. Functional rehabilitation of the dentition is the main purpose of a dental prosthesis. For that reason a FRC-FDP should be capable to withstand up to 500 N in the premolar region and 500–900 N in the molar region (Behr et al., 2002; Ozcan et al., 2005). Previous research stated that FRC-FDPs are capable of bearing posterior biting forces (Dyer et al., 2005; Garoushi et al., 2007b; Kolbeck et al., 2002; Ozcan et al., 2005; Xie et al., 2007). Taking important aspects as initial failure and buccal loading into consideration suggests that FRC-FDPs with a conventional design and even some with a modified design (FRC3 and SFRC1) maybe not indicated for use in the molar region. Nevertheless, it should be taken into consideration that the rigidity of the used test set-up negatively influences the values obtained in this study and underestimate the load-bearing capacity and subsequent clinical performance of FRC-FDPs. Load-bearing capacity values obtained in this study are situated in the lower range of those reported in literature. Previously reported load-bearing capacity values of FRC-FDPs range from 524 N (Behr et al., 2002) till 2500 N (Xie et al., 2007). This wide range of values can be explained by the differences in study design: used materials, pontic span, retainer preparation, and test set-up.

Although promising results were found during clinical studies, delamination of the veneering composite was frequently observed. In order to overcome those problems, it was proposed to improve the FRC framework in a way it becomes more rigid and gives more support to the veneering composite, which was confirmed by several studies (Behr et al., 2005; Freilich et al., 2002; Monaco et al., 2003; Xie et al., 2007). Increased rigidity of FRC frameworks can easily be obtained by increasing the amount of fibres. No significant difference was found between FRC1 and FRC2, indicating that increased framework rigidity alone seems insufficient. To increase the supportive nature of a FRC framework, it should be constructed in such a way that the veneering composite can be uniformly supported. The modified FRC frameworks tend to produce slightly higher, but not always significant different, load-bearing capacities than PFC-FDP and conventional FRC frameworks (Table 2 and Fig. 2). A previous study by Dyer et al. (2005) indicated that significant differences between reinforced and unreinforced groups occurred only above a cross-sectional FRC-volume of 43%. Analysis of the pontic cross sections of this study pointed out that the cross-sectional FRC-volume was far below 43% for all groups, except SFRC2 and SFRC3, 4.8% and 31%, respectively. Surprisingly, FDPs made of PFC showed a slightly higher load-bearing capacity, when loaded at the central fossa than FDPs with a conventional FRC framework. This observation is in agreement with earlier findings by Dyer et al. (2005) revealing that load-bearing capacity tends to be lower for low-volume FRC-FDPs in comparison to PFC-FDPs. This effect was observed for initial failure, but not for final failure. The load-bearing capacities values obtained in this study were also initial failure values. It has to be noticed that a distinguished difference with regards to failure pattern was found between PFC-FDPs and the other groups. PFC-FDPs suffered from catastrophic

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pontic failure, while FRC-FDPs suffered from delamination and veneer cracks. For that reason, one should be aware of the fact that initial and final failure is the same for PFC-FDPs. When analysing the modified FRC frameworks, it is noticed that the use of S-FRC slightly improves the performance of FRC-FDPs in comparison to an already established design (FRC3) (Xie et al., 2007). The veneered S-FRC framework (SFRC1) showed to be slightly more supportive than FRC3 when loaded at the buccal cusp. It should be noted that evaluation of the cross-sectional design revealed a discrepancy between the ideal (Fig. 4B) and the experimental design (Fig. 4A), which can partially be explained by the unfavourable handling properties of S-FRC. From a clinical point of view, one should be aware that such a design seems difficult to fabricate and proper training of dentist and dental technician is paramount. It can be hypothesized that an ideal design as depicted in Fig. 4B would produce higher load-bearing capacity values more closely to SFRC2 and SFRC3. These results showed that FRC frameworks fabricated of S-FRC produced the highest load-bearing capacity values and will probably show the least chipping and delamination during clinical function. Nevertheless, it has to be noticed that the use of non-veneered S-FRC is associated with some important drawbacks, e.g. watersorption, aesthetics, polishability, and handling, which restricts its clinical use. For that reason, groups SFRC2 and SFRC3 are not yet suitable for clinical application.

Analysis of the failure patterns of FRC-FDPs pointed out that only PFC-FDPs encountered catastrophic failure presented as pontic fracture when loaded at the central fossa. Buccal cusp loading, on the other hand, only produced cracks, which can be attributed to the more complex stress pattern generated by the applied loading. The failure pattern of conventional framework designs not only presented as cracks, but also as delamination, the latter proving the insufficient support provided by these framework designs. Failure of modified framework designs presented as cracks indicating increased rigidity and supportive nature of these designs. The one delamination that occurred in FRC3 can be attributed to less careful framework construction. Closer inspection of the particular specimen revealed that the perpendicular placed fibre bundles were too short, which compromised the support of the cusps. Although, the increase in load-bearing capacity between conventional and modified framework designs was limited, failure analysis corroborates the improved performance of modified framework designs.

Central fossa loading is the most common used loading condition in static fracture strength testing of FDPs. In this study, FRC-FDPs were loaded in the central fossa or at the buccal cusp of the pontic. Higher load-bearing capacities observed for fossa loading in comparison to cusp loading, which was in agreement with the results of Xie et al. (2007), confirms the latter to be far more demanding. This can be partially explained by the fact that the fibre is loaded during fossa loading, while the much weaker composite is loaded during cusp loading. A second explanation deals with the type of stresses induced by each loading condition. Fossa loading subjects FDPs to compressive stresses located beneath the loading point, tensile stresses located in the gingival part of the pontic as well as on the occlusal part of the connector and shear stresses located in the connector area. Cusp loading induces additional torsion stresses in the connector area and shear stresses in the cusps of the pontic. Those shear stresses in the pontic area are able to provoke chipping and delamination of the veneering composite.

The rationale for recording initial failure above final failure was based on previous research (Dyer et al., 2005; Ozcan et al., 2005). The mechanical performance of FRC-FDPs is overestimated when ultimate strength or final failure load values are considered. One should be aware of the fact that final failure loads can be 27% to 46% higher than initial failure loads (Dyer et al., 2005; Ozcan et al., 2005). It was stated by Dyer et al. (2005) that it may be more valuable to search for reinforcement and designs that elevates the initial failure load of FDPs instead of the final failure load. The damage that arises at initial failure loads presented, in this study, as cracks or delaminations. This damage weakens the FDP and may initiate further degradation. Cracks act as easy and fast access points enabling oral fluids to penetrate the FRC. Semi-IPN matrix-based FRC is more prone to watersorption in comparison to UTMA matrix-based FRC (Lassila et al., 2005) or PFC (Garoushi et al., 2007a), which can be explained by the filler content (Garoushi et al., 2007a) and hydrophilic properties of the resin matrix (Lassila et al., 2002). Watersorption induces plasticisation of the resin matrix and deteriorates the fibre-polymer interphase by possible leaching of glass forming oxides from the fibre surface and by hydrolytic degradation of the polysiloxane network formed after silanisation of the glass fibres (Abdel-Magid et al., 2005; Lassila et al., 2002). The above-described mechanisms affect the mechanical properties of FRC resulting in lower strength and elastic modulus, the latter contributes to decreased rigidity of the framework.

Rigidity of the used test set-up could have influenced the load-bearing capacities in a negative way. Fischer et al. (2004) showed that the fracture load of FDPs with rigidly mounted abutments decreased with 13% in comparison to non-rigidly mounted abutments. Additional bending stresses are induced in FDPs which are mounted in a rigid test set-up (Fischer et al., 2004). Not only could the rigidity of the test set-up, but also the elastic modulus of the abutments have had an influence on the load-bearing capacities. Non-rigidly mounted abutments with an elastic modulus close to that of natural teeth are capable of giving a more realistic representation of the oral situation. Such a

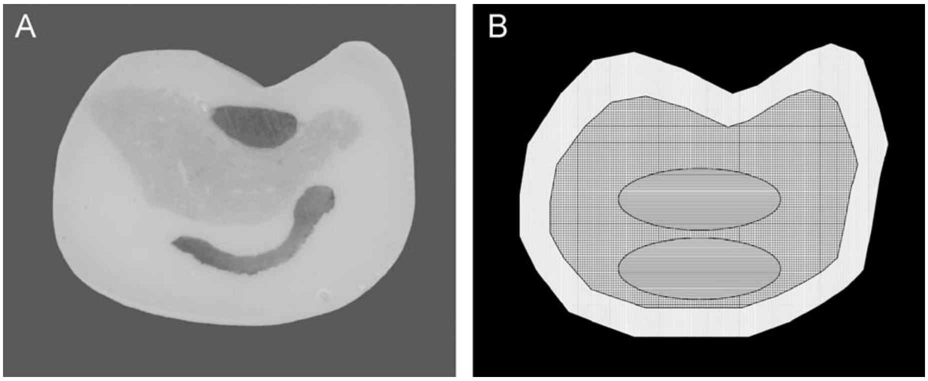

Fig. 4. Representation of the discrepancy between (A) the obtained and (B) the ideal cross section of FRC-FDP with an anatomic framework design (SFRC1).

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set-up will generate a more evenly distributed stress pattern and subsequently generate higher load-bearing capacities.

Several studies showed that modified framework designs perform better under static loading conditions. Further research should focus on the fatigue behaviour of these modified framework designs.

Conflict of interest

Professor Pekka K. Vallittu holds a full academic post at the University of Turku, but he also consults Stick Tech Ltd. in their research and development work.

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