

Influence of Retainer Design on Two-unit Cantilever Resin-bonded Glass Fiber Reinforced Composite Fixed Dental Prostheses: An In Vitro and Finite Element Analysis Study

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Purpose: The aim of this study was to evaluate in vitro the influence of retainer design on the strength of two-unit cantilever resin-bonded glass fiber-reinforced composite (FRC) fixed dental prostheses (FDP).

Materials and Methods: Four retainer designs were tested: a proximal box, a step-box, a dual wing, and a step-box-wing. Of each design on 8 human mandibular molars, FRC-FDPs of a premolar size were produced. The FRC framework was made of resin impregnated unidirectional glass fibers (Estenia C&B EG Fiber, Kuraray) and veneered with hybrid resin composite (Estenia C&B, Kuraray). Panavia F 2.0 (Kuraray) was used as resin luting cement. FRC-FDPs were loaded to failure in a universal testing machine. One-way ANOVA and Tukey's post-hoc test were used to evaluate the data. The four designs were analyzed with finite element analysis (FEA) to reveal the stress distribution within the tooth/restoration complex.

Results: Significantly lower fracture strengths were observed with inlay-retained FDPs (proximal box: 300 ± 65 N; step-box: 309 ± 37 N) compared to wing-retained FDPs ($p < 0.05$) (step-box-wing: 662 ± 99 N; dual wing: 697 ± 67 N). Proximal-box-, step-box-, and step-box-wing-retained FDPs mainly failed with catastrophic cusp fracture (proximal box 100%, step-box 100%, and step-box-wing 75%), while dual-wing-retained FDPs mainly failed at the adhesive interface and/or due to pontic failure (75%). FEA showed more favorable stress distributions within the tooth/restoration complex for dual wing retainers.

Conclusion: A dual-wing retainer is the optimal design for replacement of a single premolar by means of a two-unit cantilever FRC-FDPs.

Keywords: fiber-reinforced composite, cantilever, fixed dental prosthesis, static fracture strength, finite element analysis.

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Single-tooth replacement in the anterior and premolar region is more often required to improve esthetics than for functional reasons. Contemporary dentistry offers a broad range of treatment modalities for single tooth replacement, eg, autogenous tooth transplantation, removable dental prostheses (RDPs), fixed dental prostheses (FDPs), and implants. Although autogenous tooth transplantation and RDPs are viable treatment options from the point of view of preserving tooth tissue and reduction of cost, their indication and use are limited.^{43,47} Instead, three-unit fixed dental prostheses and implant-retained crowns are acknowledged as the treatment of choice.^{36,42} In cases with limited bone height and/or width and extensively restored adjacent teeth, a FDP is preferred, while implant-retained crowns are chosen when neighboring teeth are free of restorations and/or caries. However, not all single-tooth

Table 1 Materials used for static fracture strength test of two-unit cantilever resin-bonded FRC-FDPs

Product	Composition	Manufacturer	Lot number
Estenia C&B EG Fiber	UTMA, silanized E-glass fibers, ultra fine silica filler	Kuraray; Okayama, Japan	0003AB
Estenia C&B Dentine A2	UTMA, bis-GMA, TEG-DMA, glass ceramic, Al ₂ O ₃	Kuraray	00219A
Panavia F2.0	EDII primer and luting resin	Kuraray	41170
ED II Primer	Primer A: HEMA, MDP, 5-NMSA, water, accelerator Primer B: 5-NMSA, accelerator, water, sodium benzene sulphinate		
Luting resin	Base paste: hydrophobic aromatic (and aliphatic) dimethacrylate, hydrophilic dimethacrylate, sodium aromatic sulfinatate, N,N-diethanol-p-toluidine, function- alized sodium fluoride, silanized barium glass Catalyst paste: MDP, hydrophobic aromatic (and aliphatic) dimethacrylate, hydrophilic dimethacrylate, silanized silica, photoinitiator, dibenzoyl peroxide		
Clearfil Porcelain Bond Activator	Hydrophobic dimethacrylate, MPTS, bis-PMA	Kuraray	00158B
Clearfil SE Bond Primer	MDP, HEMA, hydrophilic dimethacrylate, dl-cam- phorquinone, water	Kuraray	00407A
UTMA: urethane tetramethacrylate; bis-GMA: bisphenol-A-glycidyl dimethacrylate; TEG-DMA: triethylenglycol dimethacrylate; MDP: 10-methacryloyloxyde- cyl dihydrogen phosphate; HEMA: 2-hydroxyethyl methacrylate; 5-NMSA: N-methacryloyl 5-aminosalicylic acid; MPTS: 3-methacryloxypropyl trimethoxy silane; bis-PMA: bisphenol-A-polyethoxy dimethacrylate.			

gaps can be restored by means of conventional FDPs or implant-retained crowns.

In cases involving patients with diastema less than 7 mm and caries-free adjacent teeth, or those with limited financial resources, resin-bonded fixed dental prostheses (RB-FDP) have proved to be a reliable alternative.¹⁷ Nevertheless, metal ceramic RB-FDPs have some drawbacks, such as the greyish appearance of abutment teeth caused by shine-through of metal retainers. Another common problem with RB-FDPs is early loss of retention caused by the number of abutments and a lack of retentive and resistant preparation.^{5,14,17}

Clinical research has shown that in order to improve retention, resistance, and the subsequent longevity of RB-FDPs, the abutment teeth need more extensive preparation; this should include not only complete palatal or lingual coverage with 180-degree wraparound, but also chamfer, occlusal or cingulum rests, and proximal guide planes and grooves.^{2,5,13,17,45}

In particular, it is often the case that only one of the retainers debonds.³⁷ After removal of the debonded retainer, many of these partially debonded bridges have been successfully converted into a cantilever design.¹⁰ Dynamic

tooth contacts are believed to induce twisting and shear forces which cause retainers in fixed-fixed RB-FDPs to be dislodged; this is referred to as biting the tooth out of the retainer.^{5,6,14,23,45} The free-standing nature of two-unit cantilever RB-FDPs is thought to reduce or even eliminate these adverse stresses on the adhesive interface during function.^{5,6,45} Clinical research has demonstrated that two-unit cantilever RB-FDPs performed as well as or even better than their three-unit fixed-fixed counterparts.^{7,8,10,14,23}

Over the last few years, fiber-reinforced composites (FRC) have become more popular.¹⁹ The introduction and subsequent development of adhesive dentistry established the paradigm shift from G.V. Black's "extension for prevention"⁴ to minimally invasive dentistry.^{33,34} The interest in metal-free FDPs was stimulated particularly by the less acceptable esthetics of metal ceramic FDPs, and by growing awareness in the dental profession of allergic reactions to dental alloys.³⁹ This continuous search for less invasive and metal-free treatments focused attention on fiber-reinforced composite fixed dental prostheses (FRC-FDPs), whose current popularity can be attributed to the fact they can be fabricated not only in the dental laboratory, but also chairside by the dentist. Clinical trials with evaluation pe-

riods of up to five years have demonstrated that FRC-FDPs are indeed a suitable treatment option:^{20,21,30,44} even longevity of at least ten years now seems reasonable.²⁴

Dentistry has now entered an era in which conservation of dental tissue and esthetics are of utmost importance when restoring the dentition. A two-unit cantilever resin-bonded FRC-FDP is one such conservative and esthetic alternative.

To our knowledge, only three publications have reported on this treatment modality for anterior single-tooth replacement.^{12,27,28} A clinical report by Culy et al¹² concluded after only 10 months of observation that direct cantilever resin-bonded FRC-FDPs could be a viable option for replacing anterior teeth. Li et al^{27,28} determined failure load, deflection, and failure location, and identified the role of the fibers and the adjacent teeth in an in vitro study and in a finite element analysis (FEA) study.

Not only two-unit cantilever metal ceramic RB-FDPs are proven to be a predictable and successful prosthetic reconstruction in the anterior and posterior region in the short to medium term,^{8,23} but also two-unit cantilever resin-bonded FRC-FDPs could be a viable anterior single-tooth replacement.¹² The aim of the present study was to investigate in vitro the influence of retainer design on the strength and stress distribution in the tooth/restoration complex of indirect two-unit cantilever resin-bonded glass fiber-reinforced composite fixed partial dentures in the premolar region. Four different retainer designs were compared. A static fracture strength test was conducted to evaluate the strength of these restorations. Stress distribution in the tooth/restoration complex was analysed by means of 3D FEA.

MATERIALS AND METHODS

Molar-borne two-unit cantilever resin-bonded FRC-FDPs were constructed according to various retainer designs. A static fracture strength test was conducted to evaluate the strength of these restorations. Stress distribution in the tooth/restoration complex was analyzed by means of 3D FEA. A recently introduced all-resin restorative system for the fabrication of laboratory-made crown-and-bridgework was used for this experiment: the restorative system was composed of a new generation hybrid resin-based composite (Estenia C&B, Kuraray; Okayama, Japan), a proprietary glass-fiber reinforcement (Estenia C&B EG Fiber) and a dual-curing resin luting cement (Panavia F 2.0, Kuraray). EG Fiber contains 48 wt% silanized E-glass fibers of 11 μm in diameter embedded in a urethane tetramethacrylate-based resin.^{26,31} Table 1 presents the composition of the materials used in this study.

Fracture Strength

Thirty-two freshly extracted human mandibular molars without caries or restorations were selected and stored in tap water at 5°C prior to use. Each tooth was positioned into a copper pipe and embedded in poly(methyl methacrylate) resin (Vertex self curing, Vertex-Dental BV; Zeist, the Netherlands) within 2 mm from the cemento-enamel junction. The

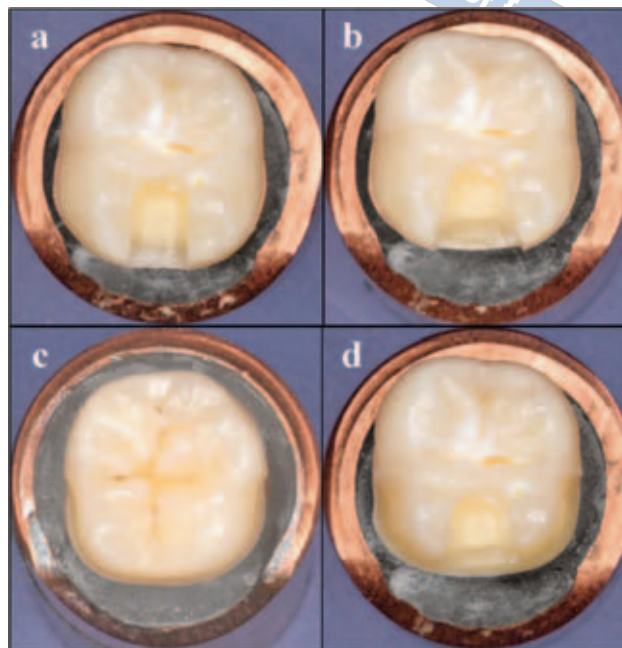


Fig 1 Different types of retainer preparation: (a) proximal box preparation (2 mm high, 2 mm wide, 4 mm deep), (b) step-box preparation (step: 2 mm high, 2 mm wide, 4 mm deep; box: 3.5 mm high, 3.5 mm wide, 1.5 mm deep), (c) dual-wing preparation (4 mm), and (d) step-box-wing preparation.

specimen were randomly divided into 4 groups ($n = 8$) and stored in tap water at 5°C until use.

Four different retainer designs were tested (Fig 1): a proximal box preparation (2 mm high, 2 mm wide, 4 mm deep), a step-box preparation (step: 2 mm high, 2 mm wide, 4 mm deep; box: 3.5 mm high, 3.5 mm wide, 1.5 mm deep), a dual-wing preparation, which consisted of a vestibular and lingual adhesive wing (4 mm long), and a step-box-wing preparation which is the combination of a step-box and a dual wing. Proximal-box-retained and step-box-retained FDPs are hereafter referred to as inlay-retained FDPs, while step-box-wing and dual-wing-retained FDPs are termed wing-retained FDPs.

All preparations were made by a single operator using conventional diamond burs (preparation set 4278 and 4384A, Komet; Lemgo, Germany) in a water-cooled, high-speed contra-angle handpiece (Kavo Dental; Biberach/Riss, Germany). The dimensions of the preparation were measured with a digital calliper (Digimatic, Mitutoyo; Kawasaki, Japan) and standardized by minor adjustments.

Two-unit cantilever resin-bonded FRC-FDPs were fabricated according to the indirect technique. The FRC framework was made of resin pre-impregnated unidirectional E-glass fibers (Estenia C & B EG Fiber), with one bundle of EG Fiber consisting of about 15,000 glass fibers. While the framework of inlay-retained FDPs was reinforced with one bundle of FRC, two bundles were used in the framework of wing-retained FDPs. Fiber-reinforcement was placed in the

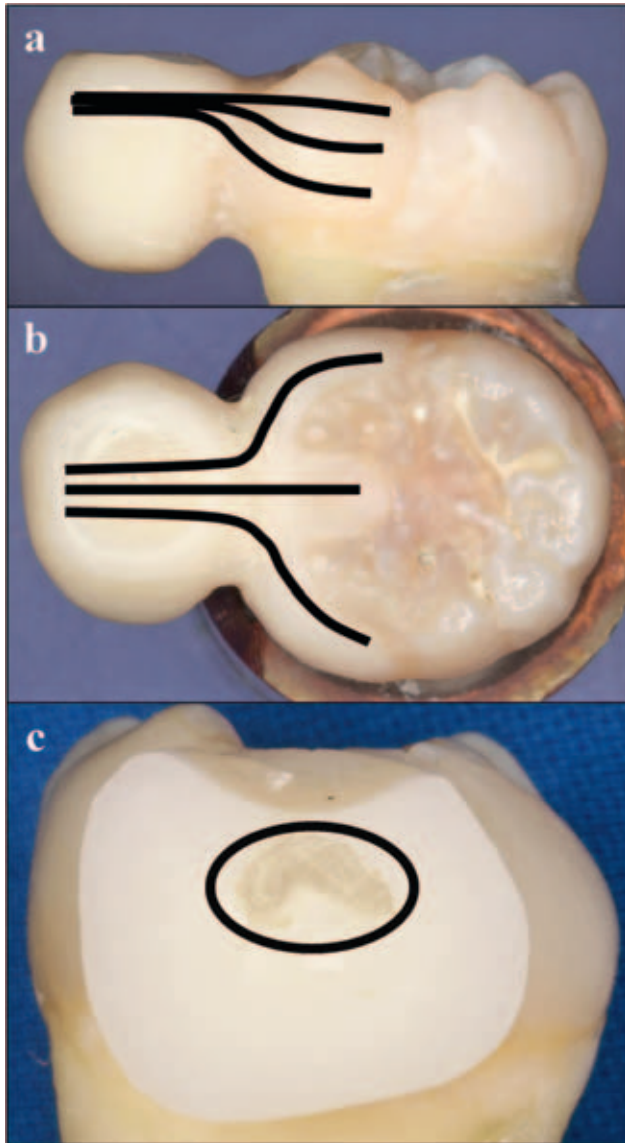


Fig 2 Fiber location (black lines) throughout a two-unit cantilever resin-bonded FRC-FDP: (a) longitudinal view, (b) occlusal view, and (c) cross-sectional view through the pontic.

area of the FDP where tensile stresses were expected to occur; for cantilever restorations, this area is situated near the occlusal surface. The fiber location throughout the FDPs is shown in Fig 2. The FRC framework was light polymerized for 10 s with a hand-held polymerization unit (Astralis 10, Ivoclar-Vivadent; Schaan, Liechtenstein) with a power output of $1000 \text{ mW} \cdot \text{cm}^{-2}$ (Curing Radiometer model 100, Demetron; Danbury, CT, USA).

The retainer and the premolar pontic were veneered in increments with hybrid particulate filler composite (PFC) for indirect use (Estenia C & B, shade dentin A2). A poly(vinyl siloxane) template was used to standardize the dimensions of each FDP (pontic: 8 mm high, 8.5 mm wide in the buc-

colingual direction, and 7 mm wide in the mesiodistal direction). The connector size differed according to the number of FRC-bundles: 5 mm wide and 5 mm high for the inlay-retained FDPs and 6.5 mm wide and 5.5 mm high for the wing-retained FDPs. Each increment was light polymerized for 10 s. The completed FDP was post polymerized by light and heat in a light furnace (Lumamat 100, Program 1, Ivoclar Vivadent) for 25 min. The FRC-FDPs were luted with an MDP-monomer containing resin luting cement (Panavia F 2.0, shade TC) according to manufacturer's instructions.

After one week of water storage at 37°C , the specimens were loaded to failure in a universal testing machine (Instron 6022, Instron; Wycombe, UK). The load was applied to the central fossa of the premolar pontic by a steel contact ball 6 mm in diameter at a crosshead speed of $1 \text{ mm} \cdot \text{min}^{-1}$.

All fractured specimens were visually examined, and their mode of failure was recorded. Adhesive failures were further examined under a light microscope (4X magnification).

Finite Element Analysis

Three-dimensional simplified finite element models were created of a two-unit mesial cantilever on a mandibular first molar. Both the molar and the pontic were 8 mm high, 10.5 mm wide in the buccolingual direction, and in the mesiodistal dimension, the molar was 11 mm and the pontic 7 mm wide. The root of the molar was 10 mm in length. The retainer designs were the same as those used for the fracture strength test. The finite element modelling was carried out with FEMAP software (FEMAP 8.10, ESP; Maryland Heights, MO, USA), while the analysis was carried out with CAEFEM 7.3 (CAC; West Hills, CA, USA). The models were composed of 57,000 to 66,000 parabolic tetrahedron solid elements. The material properties are summarized in Table 2; with the exception of the FRC, these properties were assumed to be isotropic, homogeneous, and linear-elastic. Material properties data for Estenia C & B and Estenia C & B EG Fiber were provided by the manufacturer; the data for dentin were obtained from existing literature.¹⁸ The nodes at the bottom of the root were fixed (no translation or rotation in any direction).

A load of 300 N was applied at the center of the pontic for the proximal-box-retained FDPs and the step-box-retained FDPs. For dual-wing-retained and step-box-wing-retained FDPs a load of 650 N was applied. Two stresses were calculated to establish the peel-off stress on the major attachment surfaces: the Solid Major Principle stress and the Solid S^x stress. The peel-off stress is defined as the tensile stress perpendicular to the bonding surface.

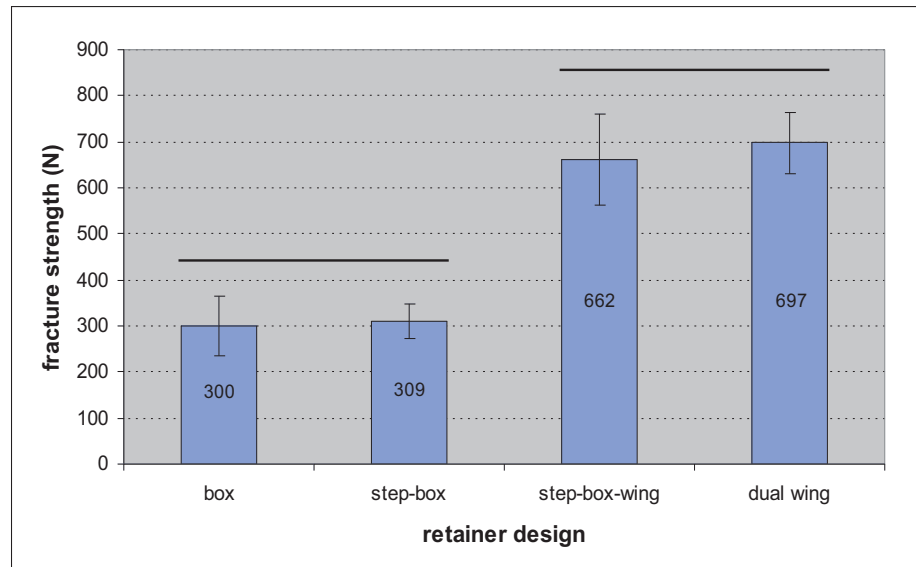
Statistical Analysis

Statistical analysis was performed with the statistical software SPSS for Windows 12.0.1 (SPSS; Chicago, IL, USA). Means and standard deviations of fracture strength for each group were calculated. One-way ANOVA followed by Tukey's post-hoc test were performed to determine the effect of retainer design on the fracture strengths observed. P-values of less than 0.05 were considered to be statistically significant.

Table 2 Material properties used in the 3D FEA model

Material	Product		Elastic modulus (GPa)	Shear modulus (GPa)	Poisson's ratio
Dentin			18		0.31
Composite	Estenia C&B		22		0.27
Fiber-reinforced composite	Estenia C&B EG fiber	longitudinal (x)	39	14	0.35
		transverse (y)	12	5.4	0.11
		transverse (z)	12	5.4	0.11

Fig 3 Bar diagram of static fracture strength (N) of two-unit cantilever resin-bonded FRC-FDPs with the mean (number) and standard deviations (error bars) for the four different retainer designs. There is no statistically significant difference between groups beneath the horizontal line (Tukey's test $p < 0.001$).



RESULTS

Fracture Strength

One-way ANOVA ($F = 75.32$; $p < 0.001$; power = 1.0) revealed that the retainer design had a statistically significant effect on the static fracture strength of two-unit cantilever resin-bonded FRC-FDPs. However, Tukey's multiple comparison test ($p < 0.001$) showed only significant differences between inlay-retained designs and wing-retained designs (Fig 2). The proximal-box-retained design yielded the lowest mean fracture strength of $300 (\pm 65)$ N, which was not significantly different ($p = 0.993$) from the step-box-retained design, $309 (\pm 37)$ N. Significantly higher mean fracture strengths were obtained with wing-retained FDPs ($p < 0.001$). The dual-wing-retained design showed slightly, but not significantly ($p = 0.746$), higher fracture strength values (697 ± 67 N) than the step-box-wing-retained design (662 ± 99 N). The results of the fracture strength test are graphically presented in Fig 3.

The failure modes of the FRC-FDPs and their distribution are given in Table 3. Four modes of failure were observed: tooth fracture, FDP fracture, adhesive failure, and a com-

bination of adhesive failure and FDP fracture. The predominant modes of failure of two-unit cantilever resin-bonded FRC-FDPs are shown in Fig 4. Failure mode analysis showed that inlay-retained FDPs all failed because of tooth fracture. On the other hand, 100% of the step-box-wing-retained FDPs failed because of catastrophic cusp fracture. Only 50% of the specimens in the proximal-box-retained group and the step-box-retained group, which failed because of tooth fracture, really suffered from catastrophic cusp fracture, while in the step-box-wing-retained group, all these specimens failed because of cusp fracture. Seventy-five percent of the dual-wing-retained FDPs failed at the adhesive interface and/or due to pontic failure. Closer inspection of the adhesively fractured FDPs revealed that these specimens failed not only adhesively between luting agent and enamel, but also at the luting-Estenia interface.

Finite Element Analyses

The results of the FEA with the 300 N load on the inlay-retained FDPs and the 650 N load on the wing-retained FDPs are presented in Table 4, showing the maximum Solid Major Principle Stress in the tooth and the maximum Solid S^x

Table 3 Modes of failure for two-unit cantilever resin-bonded FRC-FDPs

Retainer design	Tooth fracture (%)	FDP fracture (%)	Adhesive failure (%)	Combination adhesive failure and FDP fracture (%)
Proximal box	8 (100)	0 (0)	0 (0)	0 (0)
Step-box	8 (100)	0 (0)	0 (0)	0 (0)
Step-box-wing	6 (75)	1 (12.5)	1 (12.5)	0 (0)
Dual wing	2 (25)	1 (12.5)	3 (37.5)	2 (25)

Table 4 Maximum stresses with the different retainer designs

	Max. Solid Major Principle Stress (MPa)	Max. Solid Sx Stress (MPa)
Proximal box	66.4	40.5
Step-box	70.0	46.3
Dual wing	52.3	48.8
Step-box- wing	56.8	44.3

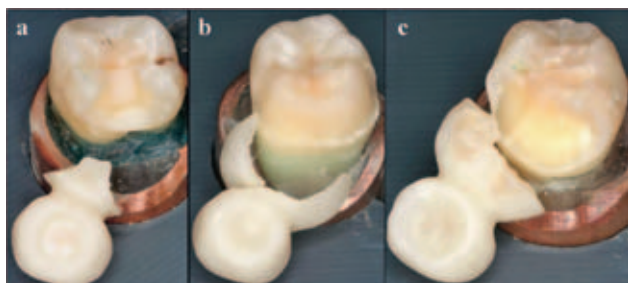


Fig 4 Predominant modes of failure of two-unit cantilever resin-bonded FRC-FDPs: (a) tooth fracture for inlay-retained design (proximal box and step-box), (b) adhesive failure for dual-wing-retained design, and (c) catastrophic cusp fracture for step-box-wing-retained design.

(peel-off stress) on the proximal contact area. Stress distribution within the tooth and the FRC framework for the four retainer designs are shown in Fig 5. For the inlay-retained FDPs, the highest tensile stresses and peel-off stresses were encountered at the proximal surface on the left and the right side of the box preparation. With step-box-wing-retained FDPs, the highest tensile stresses presented at the central groove of the occlusal surface, while the highest peel-off stresses were found at the left and right proximal surface of the box preparation. In the wing-retained FDPs, the highest tensile as well as peel-off stresses were seen in the same area, ie, in the occlusal part of the proximal surface.

DISCUSSION

The main purpose of a dental reconstruction is to functionally restore the dentition. To fulfill this requirement, a restoration should be able to withstand biting forces during mastication. Regardless of the wide range of bite forces measured, the dental community seems to have reached a consensus on the amount of load a reconstruction should be able to endure, namely 500 N in the premolar area.^{3,32} With fracture strengths up to 697 N, this study proved that only dual-wing-retained and step-box-wing-retained FRC-FDPs are able to withstand these biting forces and are consequently implementable in the premolar region. Inlay-retained FRC-FDPs, on the other hand, appeared to fail at significantly lower fracture strengths than their dual-wing-retained and step-box-wing-retained counterparts; failure loads far below 500 N make them unsuitable for the replacement of a single premolar. Dyer et al¹⁵ obtained similar results with direct three-unit FRC-FDPs and showed that slot-retained FRC-FDPs failed at lower loads than wing-retained and slot-wing-retained FRC-FDPs. An increased bonding surface can be obtained when using wings, which results in higher bond strength values because of more efficient stress transfer to the abutment teeth and lower stresses at the adhesive interface.

Compared to three-unit fixed-fixed designs, it was expected that lower fracture strengths for two-unit cantilever designs would be found. These lower values could be expected because, based on the simple beam theory, a fixed-fixed design is considered to suffer a lower amount of

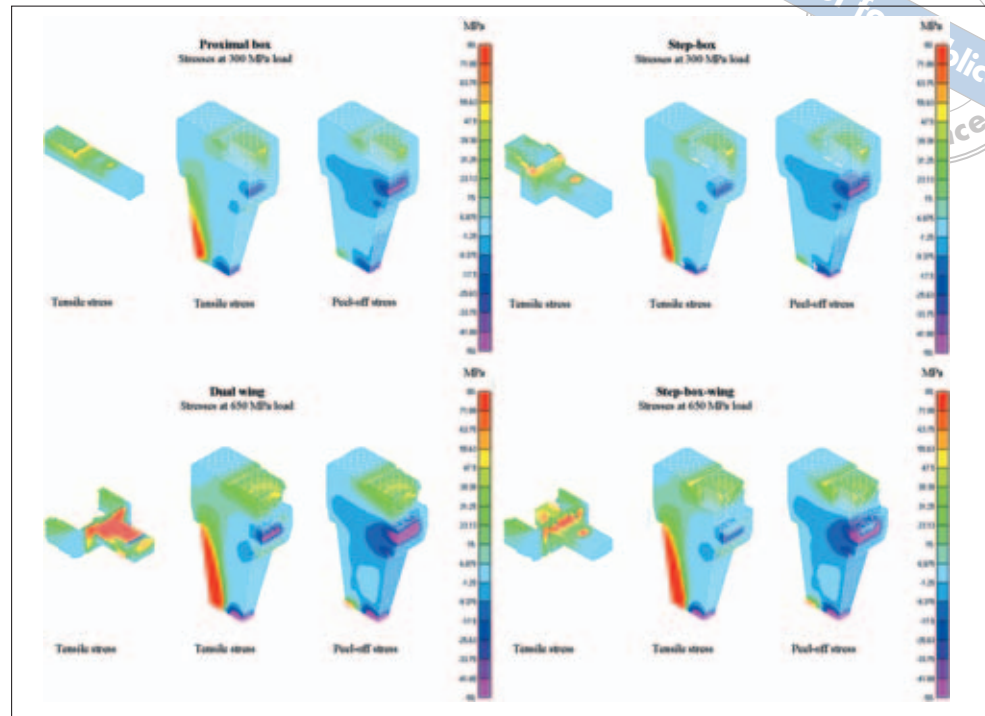


Fig 5 Distribution of tensile stresses and peel-off stresses in the tooth and the FRC framework of two-unit cantilever resin-bonded FRC-FDPs for different retainer designs.

stress than a cantilever design. Romeed et al³⁸ confirmed this assumption by investigating the mechanical behavior of a three-unit fixed-fixed FDP and a two-unit cantilever FDP with 2D FEA. However, it should be noted that they did not include the cement layer in their study.

Only one study reports on three-unit fixed-fixed inlay retained FRC-FDPs with a framework made of Estenia C & B EG Fiber and veneered with Estenia C & B; those authors obtained a slightly higher value of 943 (\pm 233) N.⁴⁶ The interabutment distance for this study corresponded to a molar replacement of 15 mm, which was double the distance of the premolar gap (7 mm) in our study. It has been previously shown that interabutment distance has an influence on fracture strength of inlay-retained FRC-FDPs.⁴⁰ Özcan et al³² reported on fracture strength values for a three-unit fixed-fixed design of a premolar replacement with comparable pontic span. They found an average fracture strength value of 1161 (\pm 428) N for conventionally prepared three-unit inlay-retained FDPs made of an Everstick framework and veneered with Tetric Ceram.

Although no significant differences were found between the two wing-retained designs, step-box-wing-retained FDPs may be slightly stronger than dual-wing-retained FDPs. The difference in predominant mode of failure between the two designs, tooth fracture within the step-box-wing-retained group vs adhesive and/or FDP failure within the dual-wing-retained group, and the results obtained by Dyer et al¹⁵ corroborates this assumption.

In this study, the amount of fibers incorporated in the FRC framework and the dimensions of the connector dif-

fered between inlay-retained FDPs and wing-retained FDPs. Inlay-retained FDPs contained only one bundle of FRC due to the lack of space. Two bundles of FRC were used for dual-wing-retained FDPs, where each wing contained one bundle of FRC. In addition, two bundles of FRC were used for step-box-wing-retained FDPs. In this design, the inlay contained one bundle of FRC, while each wing contained half a bundle of FRC. The use of two bundles of FRC caused an increase in connector-size for wing-retained FRC-FDPs. Although the fracture strength values of wing-retained FDPs were significantly higher than those of inlay-retained FDPs, fracture mode analysis suggests that the difference in connector size and fiber amount were not the factors that caused the increase in fracture strength. The FRC-FDPs never failed due to fracture of the connector or the retainer. Nevertheless, an increase in fiber amount as well as of connector size can have a beneficial effect on the strength of FRC-FDPs.^{1,16,27,28}

Recent in vitro research by Li et al^{27,28} revealed the beneficial effect of adjacent teeth on anterior cantilever resin-bonded FRC-FDPs. Higher fracture strength values were obtained in specimens with adjacent teeth.²⁸ The observed effect was more important for nonreinforced than for reinforced specimens: 47% vs 11%, resp. This finding was in agreement with the results of a subsequently conducted FEA study, where lower stresses occurred in a model with adjacent teeth.²⁷ Such a set-up obviously more closely resembles clinical reality and suggests that a certain amount of occlusal loading can be transferred to the adjacent teeth. With this in mind, and based on the fracture strength tests,

a better clinical performance of two-unit cantilever resin-bonded FRC-FDPs could be expected. The high fracture strength obtained for wing-retained FRC-FDPs in this study and the fact that the beneficial effect of adjacent teeth is more important in non-reinforced bridges^{27,28} are convincing results that two-unit wing-retained non-reinforced resin composite FDPs could be used for single tooth replacement in the premolar area.

The failure mode analysis revealed that inlay-retained and step-box-wing-retained FDPs predominantly failed because of tooth fracture, which demonstrates the weakening effect of intracoronal restorations. Previous research on fracture resistance of intact, prepared, and restored posterior teeth showed that tooth preparation and restorations like inlays not only weaken teeth, but also makes them more prone to cusp fracture.^{9,11,41}

The failure modes of the four FDP designs could be explained by 3D FEA. FDPs with a proximal box retainer or a step-box retainer all failed due to tooth fracture. In these cases, a part of the proximal wall on the left and the right of the box preparation together with the FDPs fractured out of the abutment tooth. FEA revealed that the highest tensile stresses, which are apparently of the same magnitude as the strength of the tooth material, are in the same area. The highest peel-off stress is apparently lower than the bond strength between the tooth and the retainer. Highest tensile stresses in step-box-wing-retained FDPs presented at the central groove of the occlusal surface, where tooth fracture started, which made this design more prone to catastrophic cusp fracture. Dual-wing-retained designs predominantly failed due to debonding, pontic fracture, or a combination of the two. In the FEA, the wing-retained designs showed the lowest tensile stresses, which are apparently below the strength of the dental tissue, and the highest peel-off stresses of all four designs were found in the occlusal area of the proximal surface, which explains why they often debonded. Comparison of the stress distribution in all four FRC frameworks revealed that the wing-retained designs suffered the largest amount of stress, which was far below the flexural strength of EG fiber. The large amount of stress in the FRC frameworks suggests that proper fiber reinforcement and framework design is of utmost importance for wing-retained FDPs.

The elastic modulus of 39 GPa for the EG fiber, as provided by the manufacturer, is higher than the 25 GPa obtained from three-point flexure testing.²⁶ Nevertheless, an elastic modulus of 39 GPa seems correct, as a similar value, provided by a different manufacturer, is cited by Magne et al.²⁹ In the 3D FEA model, the elastic modulus of the FRC was decreased from 39 GPa to 20 GPa. This resulted in an increase of the maximum solid major principle stress from 52.3 MPa to 59.8 MPa and an increase of the maximum Solid S^x stress from 48.8 MPa to 56.3 MPa. Thus, fiber-reinforced composite with a lower elastic modulus results in higher stresses at the adhesive interface, as well as in the tooth. Lower fracture strengths and more adhesive failures can be expected. The same principle applies to PFC-FDPs.

It should be noted that the FEA models have some limitations, eg, a simplified tooth model only composed of dentin, and a rigid adhesive interface instead of an elastic

resin luting cement interface. The FEA model was created for revealing the major stress distribution in order to explain failure mode. The highest tensile stresses (52.3 MPa to 70.0 MPa) in the tooth were in the range of the ultimate strength of dentin found in the literature, that is, 54 MPa when tubules were oriented parallel to the shear plane and 92 MPa when tubules were oriented perpendicular to the shear plane.²⁵ The highest peel-off stresses (40.5 MPa to 48.8 MPa) at the adhesive interface slightly exceeded the microtensile bond strength of Panavia F to enamel and dentin, 38.8 MPa and 17.5 MPa, respectively.²² Although the tooth in our FEA model was composed only of dentin, the restorations in our specimen were mainly bonded to enamel. It must be noted that the microtensile bond strength values reported by Hikita et al²² were obtained with rectangular specimens trimmed to a cylindrical hourglass shape with a diameter of 1.2 mm at the biomaterial/tooth interface. It was determined by Phrukkanon et al³⁵ that microtensile bond strength values obtained with cylindrical hourglass shaped specimen underestimate real bond strength due to stress concentration at the biomaterial/tooth interface. Three-dimensional FEA models showed that the highest peel-off stresses occurred at surfaces where the restorations were luted to enamel. Visual inspection of the fractured specimen revealed that adhesive failures mainly presented at the bond surface between enamel and resin luting cement (Panavia F). Thus, we can conclude that 3D FEA was able to explain the observed predominant failure modes.

The choice for a dual-wing retainer was based on the fact that such retainers are believed to transfer and subsequently bear forces from dynamic tooth contacts more effectively than one-wing retainers. Both wings were 4 mm in length in order to establish a 180-degree wraparound, which improved the retention and resistance of resin-bonded bridges.⁴⁵ However, future research should determine whether tooth preparation to such a large extent is necessary. The step-box-wing retainer was tested because small mesial and/or distal Class 2 restorations are frequently present in (pre)molars. Based on the results of this study, a dual wing is the preferred retainer for replacing a lost premolar by means of an indirect two-unit cantilever resin-bonded FRC-FDP; the strength is comparable to that of the step-box-wing retainer and the dominant mode of failure is debonding instead of cusp fracture. For these reasons, we advise that existing restorations not be incorporated into an indirect two-unit cantilever resin-bonded FRC-FDPs. Future research is needed to confirm this hypothesis. In such cases, we propose the following procedure. To start with, the tooth should be restored with a direct resin composite restoration suitable for use in the posterior area. Tooth preparation and impression taking can be done immediately proceeding restoration at the same visit or during the course of a second visit. The dual-wing-retained FRC-FDPs should be placed, under rubber-dam isolation, at the last visit.

The limitations of this study must be recognized. The fact that the specimens were not subjected to artificial aging, such as thermocycling and/or mechanical loading, should be seen as a drawback. Static fracture strength testing after artificial aging more closely resembles clinical

reality than without artificial aging. Moreover, this study was limited to high static loads, while in clinical conditions, dental reconstructions are also exposed to low cyclic loading or fatigue loading. Because failure of dental restorations is quite often caused by fatigue loading, future in vitro research should focus on fatigue. It is difficult to correlate in vitro tests in general and fracture strength and fatigue tests in particular to clinical reality. Therefore, the authors recommend evaluation of this treatment modality in a properly designed randomized clinical trial before introduction into general dental practice.

CONCLUSION

Within the limitations of this study, it was concluded that a dual-wing retainer is the optimal design for replacement of a single premolar by means of a two-unit cantilever resin-bonded FRC-FDP. The strength is comparable with that of the step-box-wing-retained FDPs, while the predominant failure is debonding instead of catastrophic cusp fracture, which is more favorable.

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Clinical relevance: Indirect two-unit cantilever resin-bonded FRC-FPDs are a possible treatment modality for single-tooth replacement in the premolar region. A dual-wing retainer seems to be the preferred retainer design.