

Fracture Strength of Direct Surface-retained Fixed Partial Dentures: Effect of Fiber Reinforcement *versus* the Use of Particulate Filler Composites Only

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This study compared the fracture strengths and analyzed the failure types of direct, surface-retained, anterior fixed-partial-dentures (FPD), reinforced with four types of fiber-reinforced composites (FRC) *versus* non-fiber-reinforced FPDs made of three particulate filler composites (PFC). To this end, surface-retained anterior FPDs (N=70, 10 per group) were prepared and divided into seven experimental groups, where Group 1: FRC1 (everStick)+PFC1 (Clearfil Photo Posterior); Group 2: FRC2 (BR 100)+PFC1; Group 3: FRC3 (Interling)+PFC1; Group 4: FRC4 (Ribbond)+PFC1; Group 5: PFC1 only; Group 6: PFC2 only (Sinfony); and Group 7: PFC3 only (Estenia). Fracture strength test was performed after water storage at 37°C for three days (universal testing machine, 1 mm/min). No significant differences were found among the four FRC types veneered with PFC1 ($1490 \pm 548 - 1951 \pm 335$ N) ($p < 0.05$) (ANOVA, Tukey's test). Among all the experimental groups, PFC1 presented a significantly higher mean value (2061 ± 270 N) than PFC2 (1340 ± 395 N) ($p < 0.05$) and all the other FRC-reinforced groups ($p < 0.05$). Complete pontic fracture was 100% and 70% for PFC2 and PFC3 respectively.

Keywords: Fiber-reinforced composite, Fracture strength test, Particulate filler composite

INTRODUCTION

In current dental practice, the treatment philosophy is based on the least invasive approach whereby intact tooth tissues are conserved as much as possible. As such, restoration possibilities for missing anterior teeth include a removable denture, or a conventional metal-ceramic, resin-bonded fixed partial denture (FPD) or an implant-supported one. Each of these techniques has its own advantages and disadvantages, and some of the latter may include technical complexity coupled with biological and financial repercussions.

Besides conventional dental restorations, tooth-colored fiber-reinforced composites (FRC) have also been suggested for replacement of missing anterior or posterior teeth because of their ability to withstand masticatory forces¹⁻⁸. Riding on this acclaim, a growing number of FRC materials have been introduced to the dental market. They are applicable for either direct or indirect dental restorations. In direct applications, bond strength of resin composites to enamel and dentin has been favorably documented to be superior — although bond strength to dentin is lower than that to enamel⁹. In indirect applications, on the other hand, the adhesion of resin cement to prepolymerized resin composite covering the fibers has been reported to be less favorable¹⁰. In the latter case, a solution is found in surface-retained FRC FPDs which bear two apparent immediate advantages. First, they require no preparation of sound tooth tissue — which fits perfectly with the minimal intervention philosophy, especially in situations

where the positional relationship between the maxilla and mandible is appropriate. Moreover, by virtue of the etched enamel, better adhesion is yielded between the veneering composite — which surrounds the fibers — and the tooth surface.

Fibers are usually impregnated with monomers, polymers, or a combination of both in order to achieve good adhesion with the veneering composite resin¹¹. Effective preimpregnation also allows the matrix to increase the surface wetting property of the fibers and helps to keep the fibers in close contact within a fiber bundle¹². Furthermore, good impregnation of fibers with the surrounding monomer matrix is important since fiber reinforcement is successful only when the loading force could be transferred from the resin matrix to the fibers¹³. Pre-impregnated systems usually involve monomers like urethane dimethacrylate (UDMA), urethane tetramethacrylate (UTMA), bisphenol glycidylmethacrylate (Bis-GMA), or polymethyl methacrylate (PMMA) either already impregnated by the manufacturer or readily performed by the clinician. Rigidity and strength of dental appliances made from FRCs are dependent on the polymer matrix of the FRC and the type of fiber reinforcement¹⁴. On the use of ultrahigh molecular weight polyethylene (UHMWPE) fibers, evidence still lacks whether they can be used to fabricate durable FRC restorations¹⁵⁻¹⁹. In particular, criticism has been focused on the inadequate interfacial adhesion between polyethylene fibers and dental polymers¹⁸.

Studies revealed that the impact strength of PMMA was improved by the incorporation of untreated UHMWPE fibers¹⁵. As for the concern

about poor adhesion of polymers to UHMWPE fibers, it has been improved by various types of electrochemical "plasma" treatments. However, this type of surface treatment has not increased the bond strength of resin composites to treated UHMWPE fibers as compared to untreated fibers¹⁵). On this note, questions still exist whether UHMWPE fibers can be used to fabricate high-quality dental composite structures^{17,18}).

The development and improvement of particulate filler composites (PFC) resulted in high-strength polymeric materials due to the increased filler content. Filler particles of different sizes and volume contents are added to the polymer matrix. One of the latest developments, the so-called hybrid ceramic, contains a mixture of high quantity of ultrafine fillers (particle size: 0.02 μm) loaded into a microfilled (particle size: 2 μm) resin matrix. In this manner, a high volume percentage of fillers could be embedded in the resin matrix.

To date, studies that evaluated and compared inlay-retained FPDs have been conducted²⁰⁻²²). However, no studies have been undertaken to compare the mechanical properties of surface-retained FRC FPDs with various PFCs or using non-fiber-reinforced PFCs only. It is noteworthy that with the recently introduced microfilled composites, properties of high strength could be achieved in indirect restorations where polymerization takes place in a special light curing device under heat and light. As these PFC materials also involve camphorquinone, it was hypothesized that direct light polymerization using halogen lamps could also lead to sufficient polymerization of these PFCs. If this were so, then these PFCs could similarly be used for direct FPD applications with comparable fracture strength.

Therefore, the objectives of this study were twofold: (1) to compare the fracture strengths of direct surface-retained anterior FPDs, reinforced with four types of fibers preimpregnated with UTMA, PMMA/Bis-GMA, or Bis-GMA monomers, versus direct non-fiber-reinforced FPDs made of three types of PFCs with varied monomer matrices and filler contents; and (2) to analyze the types and sites of failure.

MATERIALS AND METHODS

Tooth specimens

A total of 140 (70 central incisors, 70 canines) caries-free, freshly extracted maxillary human teeth were used in this study. The teeth were stored in distilled water with 0.1% thymol solution at room temperature. All teeth were evaluated under blue light transillumination to make sure that the enamel was free of crack lines. Specimens were stored in distilled water up to three months until the experiments. The enamel surfaces were cleaned and pol-

ished using water and fluoride-free pumice with a prophylaxis brush, rinsed with water, and dried using an air syringe. Using a silicone mold and leaving a space of 7.0 mm between the central incisor and canine, which was approximately the mesiodistal size of a lateral incisor, the teeth were embedded in autopolymerized polymethyl methacrylate (Vertex, Zeist, The Netherlands) resin blocks up to their cementoenamel junction.

Enamel surfaces to be bonded were roughened with a tungsten carbide bur (Komet No. H22AGK.314, Lemgo, Germany, Lot No. 349934) using a high-speed handpiece under water irrigation and acid-etched with 38% H_3PO_4 (TopDent Gel, TopDent, Vasteras, Sweden, Lot No. 031111) for 60 seconds²³). After rinsing with water and air-drying, an intermediate adhesive resin (Quadrant UniBond, Cavex, Haarlem, The Netherlands, Lot No. 010044) was applied onto the surfaces using a microbrush, gently air-dried, and light-polymerized (Demetron LC, SDS Kerr, Orange, CA, USA; light intensity: 600 mW/cm^2) for 20 seconds. Concave, soft metal bands (Sectional Matrix System, Danville Engineering, CA, USA, Lot No. 88039) were used as a pontic forming aid.

Experimental groups

Table 1 lists the brand names, codes, compositions, manufacturers, and batch numbers of the materials used in this investigation. PFC was incrementally applied onto the prepared enamel surface and light-polymerized for 40 seconds in all directions (Fig. 1).

In groups involving fiber reinforcement, a thin layer of flowable composite resin (StickFlow, Stick Tech, Finland, Lot No. 302591) was applied onto the tooth surface and light-polymerized together with the FRC material for 40 seconds. At the same time, gentle pressure was exerted over the fiber using a silicone instrument (Silicone Refix, Stick Tech, Finland). FRC4, the non-impregnated fiber, was impregnated using an intermediate adhesive resin (Quadrant UniBond). Fiber surfaces were thus completely covered with composite resin, and each layer was again light-polymerized for 40 seconds in all directions.

In groups without any fiber reinforcement, the whole restoration was completed with the incremental application of the individual PFC. Subsequently, pontic dimensions were measured with a digital micrometer (accurate to 0.005 microns) (Mitutoyo Ltd., Andover, UK) and kept at 6 mm in the buccolingual (BL) direction, 6.5 mm in the mesiodistal (MD) direction, and 9 mm in the cervico-occlusal (CO) direction.

Finally all restorations were finished using fine diamond burs (model number 012, Intensiv, Grancia, Switzerland) to remove the excess PFC and polished with coarse, medium, fine, and ultrafine finishing

Table 1 Brand names, codes, compositions, manufacturers, and batch numbers of the materials used in this study. FRC1, 2, 3, and 4 were veneered with PFC1

Brand name	Code	Composition	Manufacturer	Batch number
everStick	FRC1	E-glass/PMMA/Bis-GMA	StickTeck Ltd, Turku, Finland	000088
BR-100	FRC2	E-glass/UTMA	Kuraray, Okayama, Japan	00006A
interling	FRC3	E-glass/Bis-GMA	Angelus, Londrina, Brazil	2199
Ribbon	FRC4	Ultra High Molecular Weight Polyethylene	Ribbon, Seattle, USA	9543
Clearfil Photo Posterior	PFC1	Silanated silica Silanated colloidal silica Prepolymerized organic filler containing colloidal silica Urethane tetramethacrylate Bisphenol A diglycidylmethacrylate Triethyleneglycoldimethacrylate dl-Camphorquinone	Kuraray, Okayama, Japan	00165A
Sinfony	PFC2	Monomer matrix HEMA/diacrylate 10-30%(octahydro-4,7-methano-1H-indenediyl ethylene)diacrylate) Inorganic fillers: Strontium-aluminium borosilicate glass, silicon oxide(50 wt%) Photoinitiator system	3M ESPE, St paul, MN, USA	154518
Estenia	PFC3	Urethane tetramethacrylate(UTMA), Lanthanum Oxide(filler)(92 wt%)	Kuraray, Okayama, Japan	D3-DA3-3

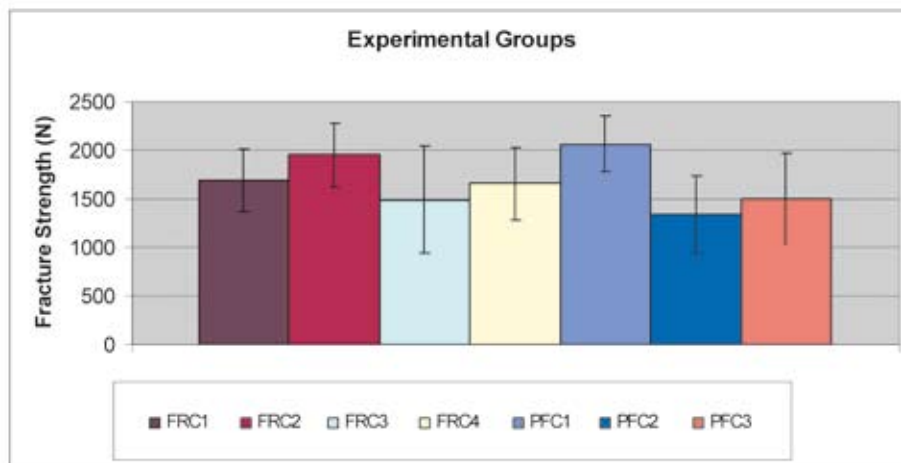


Fig. 1 Representative photo from one of the specimens of FRC3 group showing the position of the FRC during the experimental procedure.

disks (Sof-Lex, 3M ESPE).

Fracture strength test

After water storage in distilled water at 37°C for three days, specimens were subjected to fracture strength test in a universal testing machine (Zwick 1446, Ulm, Germany). Force was applied axially to the center of the pontic with a 6-mm-diameter steel ball at a crosshead speed of 1 mm/min. A sheet of tin foil (0.4 mm) was inserted between the steel ball and the pontic in order to avoid local force peaks and sliding of the load cell⁶.

Failure mode analysis

Following fracture strength tests, failures types were analyzed by two operators (OK and MÖ). Scanning electron microscope (SEM) (JSM-5500, JEOL, Tokyo, Japan) pictures were then made from representative specimens. Failure types were classified as: Type A — Detachment of veneering composite from the fiber; Type B — Complete pontic fracture; Type

C — Chipping in the veneering composite; and Type D — Fiber fracture.

Statistical analysis

Statistical analysis was performed using SPSS 12.00 (SPSS, Chicago, IL, USA). Mean values of all the experimental groups were analyzed by one-way analysis of variance (ANOVA). Due to a significant group factor ($p=0.0008$), multiple comparisons were made by Tukey-Kramer adjustment test. P values less than 0.05 were considered to be statistically significant in all tests.

RESULTS

No significant differences were found among the four FRC types veneered with PFC1 ($1490 \pm 548 - 1951 \pm 335$ N) ($p > 0.05$) (Tukey's test). PFC1 presented a significantly higher mean fracture strength value (2061 ± 270 N) than PFC2 (1340 ± 395 N) ($p < 0.05$) and all the other FRC-reinforced groups

Table 2 Mean (\pm standard deviation, SD) fracture strength (N) values of the experimental groups. *: Same superscripted letters indicate no significant differences (Tukey's test, $\alpha=0.05$). For abbreviations, see Table 1

Experimental Groups	Mean \pm SD(N)
FRC1	1693 \pm 304 ^{AB}
FRC2	1951 \pm 335 ^A
FRC3	1490 \pm 548 ^{AB}
FRC4	1658 \pm 377 ^{AB}
PFC1	2061 \pm 270 ^A
PFC2	1340 \pm 395 ^B
PFC3	1503 \pm 475 ^{AB}

Table 3 Failure types and distributions in percentage for each experimental group. Type A=Detachment of veneering composite from the fiber; Type B=Complete pontic fracture; Type C=Chipping in the veneering composite; Type D=Fiber fracture. For abbreviations, see Table 1

	Type A	Type B	Type C	Type D
FRC1	50	10	40	-
FRC2	40	10	40	10
FRC3	30	10	40	20
FRC4	60	-	40	-
PFC1	-	40	60	-
PFC2	-	100	-	-
PFC3	-	70	30	-

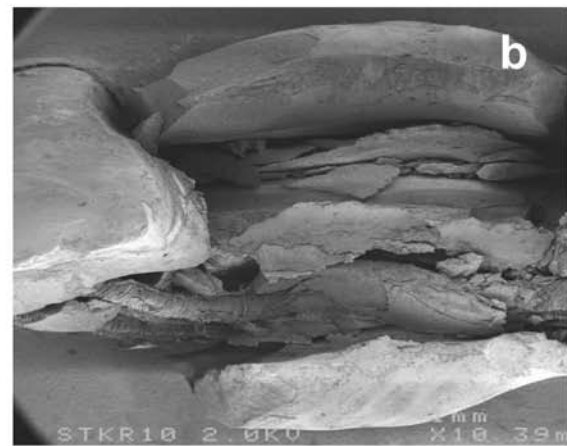


Fig. 2 Representative SEM pictures after fracture strength test: (a) everStick-Clearfil Photo Posterior FPD. Note the delamination of the veneering resin into mainly two pieces; (b) Ribbond-Clearfil Photo Posterior FPD. Note the catastrophic delamination of the veneering resin (original magnification $\times 10$).

($p < 0.05$) (Table 2).

Complete pontic fracture (Type B) was 100% and 70% for PFC2 and PFC3 respectively. In PFC1-only group, it was mostly chipping failure (60%) (Type C) (Table 3).

In FRC-applied groups, Type A or Type C failures were more common while Type B failure was the least experienced (0–10%) failure type. Further, only in FRC2 and FRC3 groups, 10% and 20% of fiber fracture were observed respectively.

Complimentary to the failure analysis, SEM pictures revealed that the delamination character of the veneering resin was more catastrophic for FRC4 when compared to FRC1 (Figs. 2a and b).

DISCUSSION

Presently, the dental market is awash with many types and architectures of fiber-reinforced composites. However, to date, only sparse clinical data have been published comparing these reinforcement methods and relating their effects to long-term clinical efficacy^{2-4,21}. In previous studies, favorable results in terms of mechanical properties were reported with the use of resin-preimpregnated, silanized glass fibers compared to non-impregnated UHMWPE fibers^{3,7}. In this study, however, no statistically significant differences were obtained between the fracture strengths of E-glass and UHMWPE fibers.

At this juncture, it should be highlighted that the mechanical properties of FRCs are influenced not only by the inherent material properties of the fibers and their polymer matrices, but also by a host of other factors — namely fiber surface treatment, quantity, direction, and position of fibers^{13,14,19}. All of this information can be derived from bar-shaped specimens prepared according to ISO norms¹³. Considering the geometry of the FPDs prepared in this study (which sought to simulate the clinical situation) and the statistically insignificant differences between the FRC materials and PFC1 and PFC2, it could be said that the dimensions of the PFC FPD were one predominant factor influencing the fracture strength data.

One other reason for the insignificant differences among the FRCs tested could be the adequate preimpregnation of the fibers with an intermediate adhesive resin or simply by virtue of the strength of PFC1 *per se*. PFC1 was composed of a urethane tetramethacrylate monomer matrix with prepolymerized organic filler containing colloidal silica filler particles. This composition must have contributed to the fracture strength of the FPDs to the extent of offsetting the variations in fiber materials. This suggestion was partially supported by the highest, yet not significantly different, mean fracture strength value obtained with PFC1 without fiber reinforcement.

Resin composite materials used in dentistry often contain polymer matrix, silanized inorganic reinforcement filler particles, and color pigments. Free radical polymerization of the bifunctional methacrylate monomer resulted in volumetric changes in the PFCs used as restorative resin composite materials or veneering composites¹¹. In this respect, filler content and consequently the elasticity modulus of the PFCs were contributing factors to the initial and final fracture strengths of the PFCs. On this same note, the flexural strength of FRC restorations might be improved with the use of new polymer formulations with high filler particle distribution (such as Estenia, Sinfony, Gradia, Sculpture) that are now commercially available²⁵. However, presently, only Sinfony is suitable for chairside use.

In the current study, a significantly lower fracture strength value was obtained with PFC2. This indicated that a relatively lower filler content (50 wt%) would cause insufficient strength to be imparted to the FPD construction, as compared to Estenia with 92 wt% filler content. In a study by Yamaga *et al.*, it became evident that resin composites containing four-functional urethane methacrylate (UTMA) had both hardness and fracture toughness greater than those of two-functional urethane methacrylate (UDMA)²⁶. As for the effect of filler content in resin composites, it tended to be linearly proportional to both hardness and fracture toughness. Therefore, two reasons accounted for the high fracture strength of PFCs containing UTMA as a monomer matrix without fiber reinforcement: the matrix composition as well as the filler content.

The abovementioned suggestion was also supported by the failure type observed in PFC2, which was exclusively complete pontic dislodgement and fracture. This failure mode suggested that fiber reinforcement played an important role in supporting and retaining the FPD even after the FPD was debonded. On the other hand, in PFC1 and PFC3, Type C failure (*i.e.*, chipping in the veneering composite) was also observed. As for FRC-reinforced groups, chiefly Type A failure accompanied with Type B and C failures were observed. Detachment of the veneering composite from the fiber indicated weak cohesive strength of the veneering PFC and poor adhesion between the PFC and FRC framework.

In FRC2 and FRC3, 10 and 20% of fiber fracture were observed respectively. However, in the other FRC groups, no fiber fractures were observed. Clinically, such failures usually require total replacement of the restorations. Conversely, in chipping cases, repair options that could prolong the service life of failed FRC FPDs could be considered²⁷. Furthermore, chipping of the veneering resin indicated that the adhesion of PFC to the etched enamel was extremely strong⁹. As for the complete fracture of

pontics, it revealed that the weakest part of the FPD was the connector area where the resin cross-section was expected to be the smallest.

In FRC3 and FRC4 groups, delamination of the veneering composite occurred in a more catastrophic manner than FRC1, where failure was predominantly separation of the veneering composite into two laminates. It should be mentioned that failure involving several laminates with final complete detachment of the veneering composite from the FRC is clinically more difficult to repair, as compared to one layer of detached or chipped veneering composite. On this issue, SEM pictures showed that FRC4 fractured into more pieces when compared to FRC1. This can be explained on the ground that FRC4, a non-impregnated fiber, was impregnated using an intermediate adhesive resin. This manual impregnation technique probably did not lead to complete wetting of the fiber, as compared to FRC1 which was preimpregnated. Another probable reason was that the intermediate adhesive resin used was not suitable for the veneering composite, although the manufacturer did not advise against any adhesive resin.

In all the experimental groups, the weakest features of the FPD restorations remained to be the pontic area and the low resistance of the veneering resin composite against occlusal forces. Unfortunately, laminated composites do not well absorb the impact energy stemming from local damage when loading direction is normal to the lamina plane. For this reason, it might seem that the load-bearing capacity of the FPD structure could be improved by increasing the filler volume fraction. However, this approach could lead to exposure of fibers, which would then impair the esthetics especially in the anterior region. Furthermore, failures in FRC1 and FRC2 were primarily in the mesiodistal direction, indicating that unidirectional fibers changed the crack path. Therefore, future studies should concentrate not only on fracture strength, but also the failure type and fracture behavior of FRCs and/or PFC FPDs.

FRC restorations are expected to withstand masticatory forces^{4,6,20}. Different testing methods and the difficulty in measuring masticatory forces have resulted in a wide range of bite force values. Stress applied during mastication may range between 441 and 981 N, 245 and 491 N, 147 and 368 N, and 98 and 270 N in the molar, premolar, canine, and incisor regions respectively²⁸. Based on these values, a restoration should be able to withstand stresses up to approximately 500 N in the premolar region and 500-900 N in the molar region. In the present study, the mean values acquired well exceeded the highest reported masticatory force of 1000 N²⁷. Direct comparison with previous studies is difficult due to differences in test plan and specimen design. Notwithstanding, the fracture strength values obtained

in this study — be it with or without fiber reinforcement — were higher than those reported by Behr *et al.*²⁰. In the latter study, glass fibers (Vectris) were used as the fiber framework in box-shaped and tube-shaped preparations and where final fracture strength values of 696 N and 722 N were obtained respectively for three-unit indirect FRC FPDs.

It is noteworthy that failures in non-reinforced FPDs particularly occurred at the pontic-abutment contact area. Therefore, FPD restorations without fiber reinforcement should not be recommended for use as long-term, durable restorations despite their considerably high fracture strengths. On the other hand, to avoid costly FRC materials for interim or semi-permanent restorations, PFC1 could be the next best option. To date, no clinical studies have reported on the performance of PFCs without fiber reinforcement. Therefore, its durability for semi-permanent treatment in real clinical situations remains unclear.

At the onset of failure, an important parameter could be the initial failure point. Some studies have established the fracture forces of FPDs by determining the initial failure from the force-deflection curve^{5,22}. Previous loading events could cause internal failures to the material and which can progress with subsequent higher levels of stress. It has been reported in earlier studies that initial failure occurs at a stress level lower than the final fracture. Unfortunately, in a clinical setting, initial failures are not easy to detect and intervention is often not introduced until catastrophic failure, including chipping failure, occurs. Against this background, comparisons among materials in this study were made based on strength values at final failure. However, it must be emphasized that FRCs and PFCs might vary and differ in their initial fracture strengths.

It is probable that the stress distribution pattern in a three-point bending test is the most common pattern of stress distribution in three-unit FPDs. This is because masticatory forces are normally concentrated on a single point, thus justifying the clinical relevancy of the fracture strength test where the load is applied on the pontic²¹. However, for successful use of FRCs in dental applications, the restoration should be of the right dimensions to withstand not only static stress, but also cyclic stresses caused by mastication. Under the influence of cyclic compressive stresses, the damage associated with delamination and the separation of fiber-reinforced layers that are stacked together to form laminates must also be taken into account. The presence of delamination may reduce the overall stiffness as well as the residual strength, leading to structural failure. Low delamination resistance causes delamination cracks. Therefore, the behavior of PFCs with and without fiber reinforcement under fatigue conditions requires

further investigation.

Fiber-reinforced FPDs are completely covered with a layer of unfilled polymer or a layer of PFC in order to obtain polishable and wear-resistant surfaces. However, it must be taken into account that water sorption of the polymer matrix also influences the flexural strength of FRCs²⁴. This study did not investigate the aging affect of water storage or thermocycling. Therefore, the results of this study represented the early failures as reported previously in clinical studies, showing that not only fatigue but that static stress could also cause fractures^{2,21,27}.

CONCLUSIONS

Within the limitations of this *in vitro* study, the following conclusions were drawn:

1. Fracture strengths of the four FRCs tested, veneered with Clearfil Photo Posterior (PFC1), did not show significant differences, but failure behavior varied among the FRCs.
2. Clearfil Photo Posterior (PFC1) without fiber reinforcement presented a significantly higher mean fracture strength value than low-filled Sinfony (PFC2).
3. The main failure type of all PFC FPDs without fiber reinforcement was complete pontic fracture. Conversely, in the FRC-reinforced groups, detachment of the veneering composite from the fiber and chipping in the veneering composite were more frequently observed.

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