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Effect of fiber-reinforced composites on the failure load and failure mode of composite veneers

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This study compared the initial and final failure loads and failure modes of indirect resin composite laminate veneers with and without fiber reinforcement. Forty intact lower canines received standard laminate preparations and were randomly assigned into four test groups (n=10). In Group 1, indirect resin composite veneers were repaired with two layers of preimpregnated bidirectional glass fiber weave and a restorative composite; in Group 2, with a layer of preimpregnated unidirectional glass fibers and a restorative composite; and in Group 3, with an experimental semi-IPN matrix composed of multidirectional short glass fibers. Indirect resin composite veneers without any fiber reinforcement were used as control (Group 4). All specimens were thermocycled and tested with a universal testing machine. On the final failure load, there were no statistically significant differences (p>0.05) among the test groups. Within each group, pairwise comparison of initial and final failure loads revealed statistically significant differences (p<0.05), except for Group 4 (p>0.05). On failure mode, unreinforced specimens showed instantaneous failure, whereas reinforced specimens mostly demonstrated elongated failure.

Keywords: Laminate veneer, Failure mode, Fiber orientation

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INTRODUCTION

Owing to an increasing demand for improved aesthetic results when restoring anterior teeth, dentists are driven to discard conservative treatment options and replace them with newly developed dental restorative materials[1)]. For several years, aesthetically satisfying results in the reconstruction of anterior teeth have been achieved with full crowns. However, this treatment option is highly destructive as large amounts of sound tooth structure are sacrificed[2-4)].

With the introduction of adhesive systems, more conservative treatment options have emerged. One of the most minimally invasive techniques is the application of laminate veneers made of either ceramics or particulate filler composites (PFC)[5)]. With PFC laminates, the other advantages include relatively low cost, inherently less brittle compared to ceramics, and to a certain extent easy to repair. However, major drawbacks include low mechanical properties[6-8)] and difficulty in bonding to highly crosslinked polymer structures[9)].

On reinforcing PFC laminates to augment their mechanical properties, attention has shifted towards fiber-reinforced composites (FRCs). FRCs have potential for use in many applications in dentistry and have gained increasing popularity for use as dental restorations[10,11)]. In the context of short-term evaluation periods, clinical studies of FRCs have shown a relatively high success rate[12-14)]. In particular, the mechanical properties of FRC restorative materials have been shown to be enhanced by either using preimpregnated fibers beneath the composite resin restorative material or reinforcing the composite material with fiber impregnation[15,16)]. Due to the high-quality needs of dental FRCs, preimpregnation of the fibers with a resin system by manufacturers has proven to be important[15,16)].

Preimpregnation is based on using either photopolymerizable dimethacrylate monomers or a combination of dimethacrylate monomer resin and linear polymer, whereby the latter forms a semi-interpenetrating polymer network (semi-IPN) after polymerization. In principle, the semi-IPN is formed from a linear polymer such as poly(methyl methacrylate) (PMMA), which is partially or totally dissolved by bi- or multifunctional monomers[17,18)]. Semi-IPN matrices are highly viscous compared to the dimethacrylate system, hence improving both the handling properties and bonding properties of the FRC after it is polymerized[16-18)]. Furthermore, with regard to the mechanical properties[19)], thermal properties[20)], bonding properties[21,22)], and shrinkage behavior[23)], it has been reported that fiber orientation is an influencing factor. Therefore, the design of FRC restorations for different purposes could be adjusted by the use of different fiber orientations.

On the repair of fractured porcelain veneers with resin composites, higher fracture loads were reported when a layer of glass fiber weave was placed between the crown and the repair resin composite[24,25)]. In particular, in the study by Vallittu[24)], a fiber weave layer was expanded over the incisal edge of the crown, thus providing a reinforced mechanical interlocking of the resin composite to the metal crown.

Therefore, the aim of the current study was to evaluate the initial and final failure loads of indirect composite laminates with and without the use of semi-IPN matrix fiber reinforcement. Additionally, the effects of fiber orientation on failure load and failure mode were evaluated.

MATERIALS AND METHODS

Tooth specimen preparation

Forty caries-free mandibular canines of comparable dimensions were selected for this *in vitro* study. The teeth were stored for a maximum of 1 month in 0.5% chloramine solution prior to use. Before use, the teeth were visually examined for structural defects and cracks, and the ones that showed any defects were excluded from the study. Adhering soft tissues and calculus deposits were removed with a hand scaler, and the bucco-palatal, mesio-distal, and cervico-incisal dimensions of each tooth were measured with a digital micrometer (Mitutoyo Corp., Tokyo, Japan; accuracy of ±0.002 mm). Each tooth was embedded in a cylindrical-shaped block, with the root mounted in a self-cure acrylic resin (Palapress, Kulzer GmbH, Wehrheim, Germany) at 2 mm apically from the cement-enamel junction (CEJ). All teeth were stored in Grade 3 deionized water, except when the experimental procedure required moisture isolation.

Prior to tooth preparation, a sectional index that could be reconstructed over the original tooth was produced using a polyvinylsiloxane material (Elite H-D, Zhermack, Badia Polesine, Rovigo, Italy). The teeth were then prepared using freehand technique by a

Table 1 Materials used in this study

Product	Type	Lot No.	Manufacturer	Composition
Vococid	Etching agent	590722	Voco GmbH, Cuxhaven, Germany	35% orthophosphoric acid
Solobond Plus primer	Primer	591582	Voco GmbH, Cuxhaven, Germany	Maleic acid, hyrophilic methacrylates, polyfunctional monomers, acetone, water
Solobond Plus adhesive	Bonding agent	591583	Voco, Cuxhaven, Germany	HEMA, polyfunctional monomers
Filtek Z250	Hybrid composite resin	6021A3,5	3M ESPE, St Paul, MN,USA	Bis-GMA, UDMA, Bis-EMA, 60 vol% fillers
Stick Resin	Unfilled resin	5509986	Stick Tech Ltd., Turku, Finland	Bis-GMA, TEGDMA
Bifix QM	Dual-cure resin luting agent	530324	Voco, Cuxhaven, Germany	Tertiary amine, Bis-GMA, fillers, camphorquinone
Experimental FRC	Multidirectional short FRC	–	–	PMMA, Bis-GMA, 22.5 wt% E-glass fiber, 55 wt% SiO_2
EverStick	Resin-preimpregnated unidirectional FRC	201.0723.ES025	Stick Tech Ltd., Turku, Finland	PMMA, Bis-GMA, E-glass fibers
EverStickNet	Resin-preimpregnated bidirectional FRC	2020218-W-0042	Stick Tech Ltd., Turku, Finland	PMMA, Bis-GMA, E-glass fibers

Bis-GMA = bisphenol A-glycidyl dimethacrylate
TEGDMA = triethylene glycol dimethacrylate
UDMA = urethane dimethacrylate
Bis-EMA = bisphenol A polyethylene glycol diether dimethacrylate
PMMA = poly(methyl methacrylate)
HEMA = hydroxyethyl methacrylate
E-glass = Electrical-glass fibers

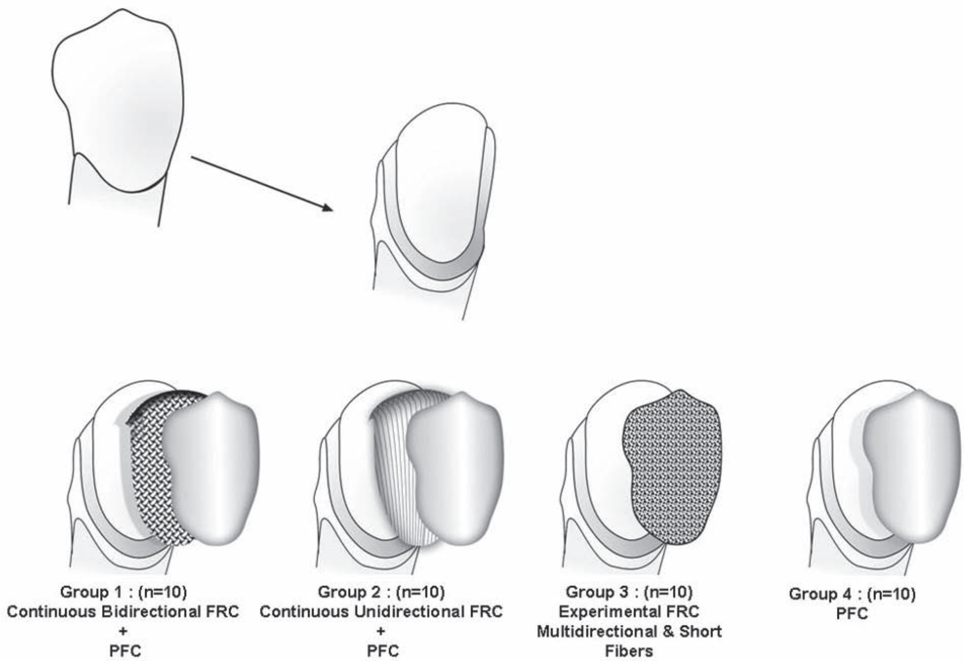

Fig. 1 Schematic illustration of the different laminate veneer preparation procedures for the test groups.

single clinician. To avoid biases caused by repetition, the teeth were prepared in three different days at separate intervals. Depth of the removed tooth structure was controlled using the index, and all preparations were within the standard of 0.5 mm. The facial and palatal surfaces were reduced to 0.5–1.0 mm, and incisal reduction was 1.5 mm. The cervical preparation ended at the CEJ. All canines were prepared with a chamfered finishing line with rounded internal line angles. The prepared surfaces were finished with aluminum oxide-embedded polishing disks (Sof-Lex, 3M ESPE, St. Paul, MN, USA), and 10 teeth were randomly assigned to each test group according to the reinforcement method.

After performing the tooth preparation, impressions for all the test groups were made using a polyvinylsiloxane impression material (Elite H-D) and cast in vacuum-mixed Type IV dental die stone (Fujirock, GC Corp., Tokyo, Japan) according to manufacturer's recommendations. Stone dies were carefully separated from the impressions, and two coats of die spacer (Belle de St. Claire, Kerr Lab Corp., Chatsworth, CA, USA) were applied 0.5 mm before the marginal finish line of the preparations.

Test groups

The PFC, FRC, bonding and luting agents used in this study are listed in Table 1. Varying fiber reinforcement approaches in the four test groups (Fig. 1) of this study are given as follows:

- Group 1 received two layers (thickness: 0.06 mm/layer) of light-polymerizable, resin-preimpregnated, continuous bidirectional FRC (EverStickNET, Stick Tech, Turku, Finland). After application and light polymerization of the fibers, restoration with a restorative composite material (Filtek Z250, 3M ESPE, St. Paul MN, USA) was performed using the polyvinylsiloxane index.
- Group 2 received one layer of resin-preimpregnated, continuous unidirectional fibers placed longitudinally along the tooth surface (EverStick C&B, Stick Tech, Turku, Finland). After application and light polymerization of the fibers, restoration with a restorative composite material (Filtek Z250, 3M ESPE, St. Paul MN, USA) was performed using the polyvinylsiloxane index.
- Group 3 comprised only an experimental semi-IPN matrix fiber composite prepared by adding 22.5 wt% of short E-glass fibers (3 mm in length) to 22.5 wt% of polymer-monomer matrix and 55 wt% of SiO_2 fillers as reported previously[26].
- Group 4 served as the control whereby PFC was used without any fiber reinforcement.

During application, the FRC and PFC increments were light-polymerized for 40 seconds each using a handheld light curing device (Optilux-501, Kerr, Danbury, CT, USA). Wavelength of the curing light ranged between 380 and 520 nm with a maximal intensity at 470 nm, and light irradiance was 800 mW/cm^2. The veneers were gently removed from the tooth dies and their polymerization was completed after 15 minutes in a light-curing oven (LicuLite, Dentsply De

Trey GmbH, Dreieich, Germany). Before cementation, an unfilled dimethacrylate resin (Stick Resin, Stick Tech, Turku, Finland) was applied to the inner surfaces of the indirect veneers and left to react for 5 minutes in a dark container.

The prepared enamel surface was first treated with an etching agent (Vococid, Voco, Cuxhaven, Germany) for 15 seconds. After rinsing and air-drying, a primer (Solobond Plus primer, Voco, Cuxhaven, Germany) was applied for 30 seconds. Then, the cavity surfaces were treated with an adhesive (Solobond Plus adhesive, Voco, Cuxhaven, Germany) for 15 seconds, air-dried, and light-cured. The veneer restorations were bonded to the prepared enamel surfaces with a dual-cure composite resin luting cement (Bifix DC, Voco, Cuxhaven, Germany), and excess cement was removed using a micro-brush. After light-curing (Elipar Free Light, 3M ESPE, Germany) for 40 seconds from the lingual, facial, and incisal sides, the margins were finished with polishing disks (Sof-Lex, 3M ESPE, St. Paul, MN, USA).

Mechanical load testing
The restored teeth were stored at 37°C for 24 hours. Then, they were thermocycled 6,000 times between 5°C and 55°C, with a 30-second dwell time at each temperature. For mechanical load testing, the specimens were loaded at 0 degree angle (Fig. 2) with a universal testing machine (Lloyd LRX, Lloyd Instruments Ltd., Farnham, UK) at a crosshead speed of 5.0 mm/min. The restored teeth were loaded until final failure occurred, whereby the loads at initial crack and final failure were recorded with Nexygen 4.0 software (Lloyd LRX, Lloyd Instruments Ltd., Farnham, UK). The crack initiation point on the load-deflection chart was determined by a sharp decrease in the loading curve.

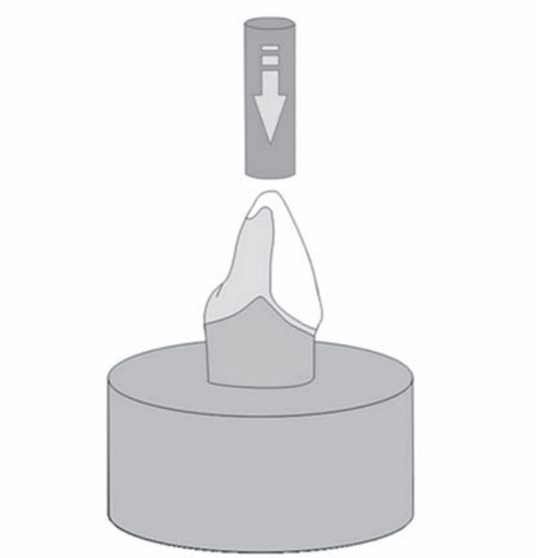

Fig. 2 Test setup used in this study.

Failure mode analysis
The failure mode of each loaded specimen was observed visually and with a stereomicroscope (Wild M3B, Leica, Heerbrugg, Switzerland). The failure modes were classified as follows: adhesive failure between laminate veneer and the tooth which is repairable, whereby less than half of the fracture is in the laminate veneer; adhesive failure between fiber reinforcement and the composite; mixed failure including partly adhesive and partly cohesive failures between tooth and laminate veneer, whereby extensive fracture in the laminate veneer was not repairable.

Statistical analysis
Individual ANOVA and Tukey's *post hoc* test were used to determine the differences among the groups at $p<0.05$ significance level using SPSS 16.0 (Statistical Package for Statistical Science, SPSS Inc., Chicago, IL, USA). Additionally, one-way ANOVA was used to determine the statistical significance of the data within each group for the initial and final failure loads.

RESULTS

Failure load
Figure 3 presents the mean initial and final failure loads for all the test groups. For the initial failure load, Group 1 exhibited the lowest mean initial failure load at 930 N, whereas Group 2 exhibited the highest value at 1160 N. Similarly for the final failure load, Group 2 (laminate veneer reinforced with unidirectional fibers) exhibited the highest value at 1792 N among the test groups. On the other hand, the lowest mean final failure load of 1295 N was recorded for Group 4 (PFC control group without any fiber reinforcement).

With regard to the initial failure load, no significant differences were found among the test groups ($p>0.05$). Similarly, for the final failure load, the differences among the test groups were not significant ($p>0.05$). However, within each test group, pairwise comparison revealed that there were

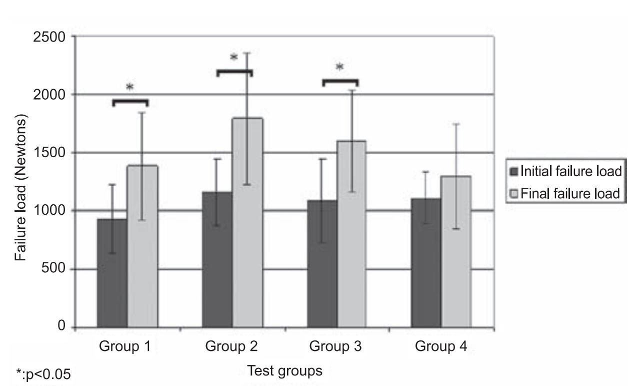

Fig. 3 Initial and final failure loads of the different test groups.

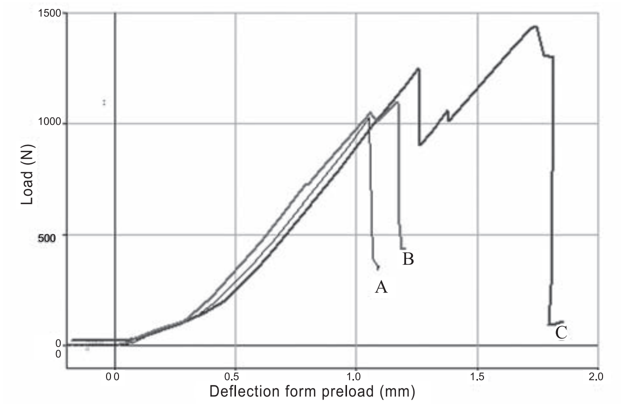

Fig. 4 Typical load-deflection graphs for A: experimental multidirectional FRC veneer (Group 3), B: bidirectional FRC (Group 1), C: unidirectional FRC veneer (Group 2).

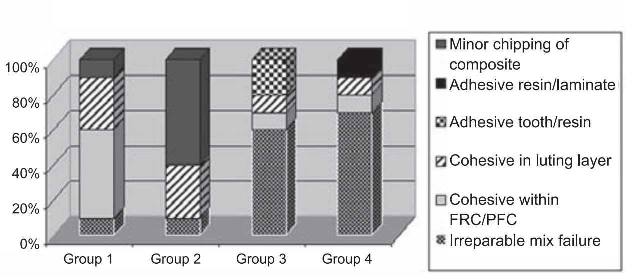

Fig. 5 Failure mode distributions of the test groups in this study.

significant differences between the initial and final failure loads ($p<0.05$) except for Group 4 ($p>0.05$).

Failure mode

The PFC control specimens (Group 4) failed instantaneously, whereas the groups reinforced with unidirectional or bidirectional fibers predominantly had a elongated failure process (Fig. 4). In the experimental short fiber-reinforced group (Group 3), at least 40% of the specimens demonstrated instantaneous failure like the PFC group while the remaining 60% exhibited a elongated failure process similar to the unidirectional or bidirectional fiber-reinforced groups.

Figure 5 presents the failure types of the different test groups. The PFC control group registered the highest number of totally or mostly fractured (irreparable) laminate veneers at 70%, followed by the experimental short FRC group at 60%. In the unidirectional fiber-reinforced group, the predominant failure mode was the detachment of the laminate veneer with some minor chippings as well as vertical microfracture lines within the PFC region of the laminate veneer (60%). On the other hand, in the bidirectional fiber-reinforced group, the predominant failure mode was cohesive failure within the FRC layer, leaving the FRC partly attached to the tooth surface and partly to the laminate veneer surface (50%).

DISCUSSION

PFC laminate veneers seemingly hold out the promise of being a cost-effective, minimally invasive treatment option. However, the use of PFC laminate veneers is highly curtailed due to reported problems on debonding, fracture, or marginal degradation at the margins[27,28].

This study was designed to evaluate the effect of fiber reinforcement on the fracture properties of indirect PFC laminate veneers. Due to the anisotropy of FRC material, its failure behavior has been known to be very complex. Previous reports have attributed the complex failure behavior to a change in the interface dynamics, whereby the latter resulted from the fibers added to the tooth-restoration interface[18,29]. The results of the current study were in good agreement with previous reports, which showed changes in failure mode despite the lack of increase in static adhesive strength[18,21,29,30]. Similarly, the final failure loads in the current study were not statistically different among the test groups — however, significant differences were seen in the load-deflection graphs as well as in their failure modes.

On the effect of fiber orientation on mechanical properties, it has been investigated and addressed in several studies[8,16,19]. Theoretically, unidirectional fibers give the highest strength by virtue of the direction of the fibers. The efficiency predicted for fiber reinforcement (Krenchel's factor) is 100% for unidirectional fibers. Therefore, if a material is likely to be loaded in one direction only, continuous unidirectional FRC will provide the optimal reinforcement. With continuous bidirectional fibers, the reinforcing effect is provided in two directions with a reinforcement efficiency of 50%, while multidirectional random fibers will render a reinforcement efficiency of 38% in a plane and 20% in three dimensions[31]. In the oral cavity, the mastication forces are complex and multidirectional in nature. Therefore, it was thought that bi- or multidirectional FRC would provide the optimal reinforcement in multiple directions. Moreover, continuous bidirectional or multidirectional short FRC can possibly mimic the biomechanics of tooth structure better than unidirectional FRC.

On the use of indirect composite resin restorations, they have been plagued by shortcomings in terms of marginal adaptation and mechanical properties[27,28,32]. Nonetheless, their superiority lies in their potential to reduce cytotoxicity attributed to incomplete polymerization. Paradoxically, the better the polymerization, the more difficult it becomes to obtain a reliable bonding to highly crosslinked structures. Therefore, the use of a semi-IPN matrix FRC could improve the bonding properties, as the mixture of cross-linked dimethacrylate and a linear PMMA matrix allows interdiffusion bonding of the new resin[17]. This bonding mechanism has been defined as secondary IPN bonding[33]. To facilitate interdiffusion bonding to the polymerized framework, further wetting of the bonding site with an adhesive resin and keeping it in a dark place for a minimum of 5 minutes were performed in this study[17,18]. This allowed monomers with the same dissolving parameter as PMMA to diffuse into the polymer matrix. In accordance with a previous report, the failure analysis of the FRC groups confirmed good adhesion between the laminate veneer and the luting agent[30]. Despite occurrences of adhesive failure between the PFC veneer and luting agent, adhesive failures between the FRC and luting agent were not common in this study.

On the use of thermocycling, it was employed in this study because it is recognized as a standard procedure for aging of dental materials[34]. Fiber orientation has been reported to affect both the polymerization shrinkage[23] and thermal expansion behavior[20] of FRCs. During the thermocycling procedure, the effect of different fiber orientations is made more acute by causing different stresses at the adhesive interface. In a previous study, it was shown that the bond strength of bidirectional or multidirectional FRC to enamel decreased significantly after thermocycling[18], whereas that of unidirectional FRC increased after thermocycling[21]. Such a contrast was attributed to their anisotropic changes in tandem with the thermal changes. On the same premise, the higher mean failure load values obtained with unidirectional fibers in this study could be partly related to the negligible expansion and shrinkage along the fibers. In other words, the continuous temperature changes did not necessarily create high stresses that impaired the mechanical interlocking of the unidirectional FRC to enamel following the thermocycling procedure[21].

On the use of FRCs, they were purported to act as a crack stopper layer at the adhesive interface[18,30]. To evaluate their efficacy as a crack stopper layer, their initial and final failure loads and failure modes were examined in this study. Initial failure signifies the beginning of the damage or breaking process. Microcracking of the matrix is often the first sign of internal damage. When failure is initiated, a part of the total strain energy is released as a wave that propagates from the failure site throughout the structure[35]. In the case of fiber-reinforced structures, as the crack propagates from one fiber to another, the microcracks and fiber breakages can absorb energy and thus decrease the energy of the final fracture. Therefore, in contrast to the PFC group which showed irreparable fracture in the laminate veneer, only some chippings and limited fractures were seen in the unidirectional FRC group. While the initial failure load values were similar among the groups, the FRC groups exhibited elongated failure whereas it was instantaneous failure for the PFC group.

In the current study, the load was applied at 0 degree angle to the incisal tip, whereby high compressive and shear forces were exerted at the interface. It must also be mentioned that in this study, the unidirectional fibers were longitudinally aligned along the substrate surface, hence resulting in higher bond reliability as compared to transversely placed unidirectional FRC[22]. Consequently, the higher bond reliability led to mere vertical fracture lines and chippings observed at the overlaying PFC layer of the unidirectional FRC group. On the other hand, for the bidirectional fibers, the predominant failure mode was interlayer detachment between the two layers of fibers, leaving one layer attached to the tooth substrate and the other to the composite laminate. This failure type could be caused by the relatively low cohesive strength between the two fiber layers as compared to the FRC-PFC or FRC-luting agent bond.

With the experimental short FRC, mixed failure behaviors were demonstrated: partly similar to PFC with instantaneous failure and partly similar to the FRC groups with elongated failure. To account for these two different behaviors, two possible explanations were suggested: the fiber volume of the experimental material was not very high and that some inhomogeneities existed within the matrix.

Despite the reinforcement advantages, the clinical application of the FRC layer was previously reported to significantly alter the color, change the hue, and increase the chroma component such that it resulted in a darker appearance[36]. Taking into account the similar final failure loads among the test groups and the differences in failure mode, the application of even a thin layer of FRC that underlies the PFC could reap beneficial outcomes in aesthetic applications.

CONCLUSION

Within the limitations of this study, it could be concluded that fiber-reinforced PFC laminate veneers demonstrated elongated failure — an outcome independent of fiber orientation.

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REFERENCES

1) Toh CG, Setcos JC, Weinstein AR. Indirect dental laminate veneers — an overview. J Dent 1987; 15: 117-124.
2) Karlsson S, Landahl I, Stegersjo G, Milleding P. A clinical evaluation of ceramic laminate veneers. Int J Prosthodont 1992; 5: 447-451.
3) Nordbo H, Rygh-Thoresen N, Henaug T. Clinical performance of porcelain laminate veneers without incisal overlapping: 3-year results. J Dent 1994; 22: 342-345.
4) Shaini FJ, Shortall ACC, Marquis PM. Clinical performance of porcelain laminate veneers. A retrospective evaluation

over a period of 6.5 years. J Oral Rehabil 1997; 24: 553-559.
5) Gresnigt MM, Özcan M. Fracture strength of direct *versus* indirect laminates with and without fiber application at the cementation interface. Dent Mater 2007; 23: 927-933.
6) Davis DM, Waters NE. An investigation into the fracture behavior of a particulate-filled bis-GMA resin. J Dent Res 1987; 66: 1128-1133.
7) Ferracane JL. Current trends in dental composites. Crit Rev Oral Biol Med 1995; 6: 302-318.
8) Garoushi S, Lassila LV, Tezvergil A, Vallittu PK. Load bearing capacity of fibre-reinforced and particulate filler composite resin combination. J Dent 2006; 34: 179-184.
9) Tezvergil A, Lassila LV, Vallittu PK. Composite-composite repair bond strength: effect of different adhesion primers. J Dent 2003; 31: 521-525.
10) Meiers JC, Duncan JP, Freilich MA, Goldberg AJ.Preimpregnated, fiber-reinforced prostheses. Part II. Direct applications: splints and fixed partial dentures. Quintessence Int 1998; 29: 761-768.
11) Freudenthaler JW, Tischler GK, Burstone CJ. Bond strength of fiber-reinforced composite bars for orthodontic attachment. Am J Orthod Dentofacial Orthop 2001; 120: 648-653.
12) Vallittu PK. Survival rates of resin-bonded, glass fiber-reinforced composite fixed partial dentures with a mean follow-up of 42 months: a pilot study. J Prosthet Dent 2004; 91: 241-246.
13) Song HY, Yi YJ, Cho LR, Park DY. Effects of two preparation designs and pontic distance on bending and fracture strength of fiber-reinforced composite inlay fixed partial dentures. J Prosthet Dent 2003; 90: 347-353.
14) Göhring TN, Schmidlin PR, Lutz F. Two-year clinical and SEM evaluation of glass-fiber-reinforced inlay fixed partial dentures. Am J Dent 2002; 15: 35-40.
15) Goldberg AJ, Freilich MA. An innovative pre-impregnated glass fiber for reinforcing composites. Dent Clin North Am 1999; 43: 127-133.
16) Vallittu PK. Flexural properties of acrylic resin polymers reinforced with unidirectional and woven glass fibers. J Prosthet Dent 1999; 81: 318-326.
17) Lastumäki TM, Lassila LVJ, Vallittu PK. The semi-interpenetrating polymer network matrix of fiber-reinforced composite and its effect on the surface adhesive properties. J Mater Sci Mater Med 2003; 14: 803-809.
18) Tezvergil A, Lassila LVJ, Vallittu PK. The shear bond strength of bidirectional and random-oriented fiber-reinforced composite to tooth structure. J Dent 2005; 33: 509-516.
19) Vallittu PK. The effect of glass fiber reinforcement on the fracture resistance of a provisional fixed partial denture. J Prosthet Dent 1998; 79: 125-130.
20) Tezvergil A, Lassila LV, Vallittu PK. The effect of fiber orientation on the thermal expansion coefficients of fiber-reinforced composites. Dent Mater 2003; 19: 471-477.
21) Tezvergil A, Lassila LVJ, Vallittu PK. Strength of adhesive-bonded fiber-reinforced composites to enamel and dentin substrates. J Adhes Dent 2003; 5: 301-311.
22) Lassila LV, Tezvergil A, Dyer SR, Vallittu PK. The bond strength of particulate-filler composite to differently oriented fiber-reinforced composite substrate. J Prosthodont 2007; 16: 10-17.
23) Tezvergil A, Lassila LV, Vallittu PK. The effect of fiber orientation on the polymerization shrinkage strain of fiber-reinforced composites. Dent Mater 2006; 22: 610-616.
24) Vallittu PK. Use of woven glass fibers to reinforce a composite veneer. A fracture resistance and acoustic emission study. J Oral Rehabil 2002; 29: 423-429.
25) Ozcan M, van der Sleen JM, Kurunmaki H, Vallittu PK. Comparison of repair methods for ceramic-fused-to-metal crowns. J Prosthodont 2006; 15: 283-288.
26) Garoushi SK, Lassila LV, Vallittu PK. Short fiber reinforced composite: the effect of fiber length and volume fraction. J Contemp Dent Pract 2006; 7: 10-17.
27) Sadowsky SJ. An overview of treatment considerations for esthetic restorations: a review of the literature. J Prosthet Dent 2006; 96: 433-442.
28) Peumans M, Van Meerbeek B, Lambrechts P, Vanherle G. Porcelain veneers: a review of the literature. J Dent 2000; 28: 163-177.
29) Fennis WM, Tezvergil A, Kuijs RH, Lassila LV, Kreulen CM, Creugers NH, Vallittu PK. *In vitro* fracture resistance of fiber reinforced cusp-replacing composite restorations. Dent Mater 2005; 21: 565-572.
30) Turkaslan S, Tezvergil-Mutluay A, Bagis B, Shinya A, Vallittu PK, Lassila LV. Effect of intermediate fiber layer on the fracture load and failure mode of maxillary incisors restored with laminate veneers. Dent Mater J 2008; 27: 61-68.
31) Vallittu PK. Strength and interfacial adhesion of FRC-tooth system. In: The second international symposium on fiber-reinforced plastics in dentistry, Chapter 1, Vallittu PK (ed.), Finland, 2001, pp.10.
32) de Andrade OS, de Goes MF, Montes MA. Marginal adaptation and microtensile bond strength of composite indirect restorations bonded to dentin treated with adhesive and low-viscosity composite. Dent Mater 2007; 23: 279-287.
33) Curtis Richard V, Watson Timothy F. Dental biomaterials: imaging, testing and modeling. Woodhead Publishing in Materials, Cambridge, England, 2008, pp.240.
34) Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. J Dent 1999; 27: 89-99.
35) Giordano M, Calabro A, Esposıto C, d'Amore, A. Nıcolais L. An acoustic emission characterization of the failure modes in polymer-composite materials. Composites Science and Technology 1998; 58: 1923-1928.
36) Sampath S, Ramachandra GS. Effects of glass fibers on light transmittance and color of fiber-reinforced composite. Dent Mater 2008; 24: 34-38.