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Fiber-reinforced Composite Substructure: Load-bearing Capacity of an Onlay Restoration and Flexural Properties of the Material

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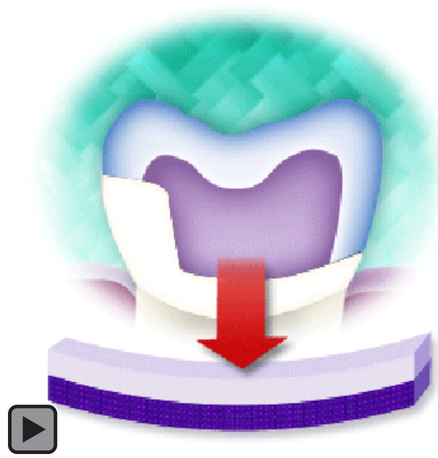

Abstract

Aim: The aim of this study was to determine the static load-bearing capacity of composite resin onlay restorations made of particulate filler composite (PFC) with two different types of fiber-reinforced composite (FRC) substructures. In addition, flexural properties of the material combination and the effect of polymerization devices were tested.

Methods and Materials: Specimens were prepared to simulate an onlay restoration, which consisted of 2 to 3 mm of FRC layer as a substructure (short random and continuous bidirectional fiber orientation) and a 1 mm surface layer of PFC. Control specimens were prepared from plain PFC. In Group A the specimens were incrementally polymerized only with a hand-light curing unit for 40 s, while in Group B the specimens were post-cured in a light-curing oven for 15 min before they were statically loaded with a steel ball.

Bar-shaped test specimens were prepared to measure the flexural properties of material combination using a three-point bending test (ISO 10477).

Results: Analysis of variance (ANOVA) revealed all specimens with a FRC substructure have higher values of static load-bearing capacity and flexural properties than those obtained with plain PFC ($p<0.001$).

Conclusion: The load-bearing capacity of all the specimens decreased after post-curing and water storage.

Restorations made from a material combination of FRC and PFC showed better mechanical properties than those obtained with plain PFC.

Keywords: Fiber-reinforced composite, FRC, load-bearing capacity, flexural properties, posterior composite restorations

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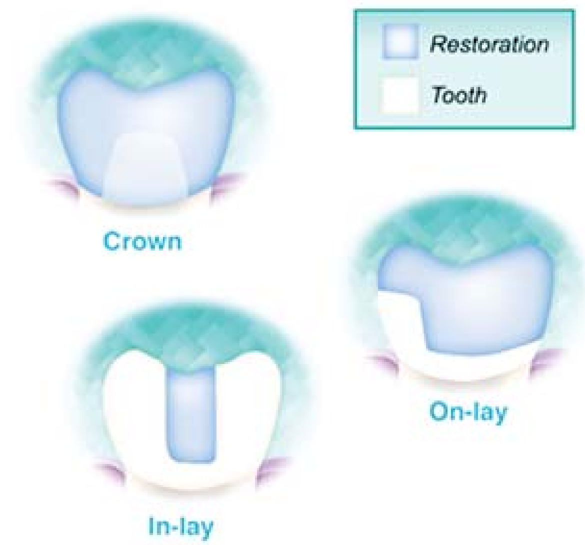
Introduction

A variety of techniques are currently available to restore teeth with moderate coronal defects in the posterior region. The selection of the proper restorative modality is dependent on the evaluation and satisfaction of numerous criteria. Routine use of metal ceramic crowns instead of gold alloy partial crowns and onlay restorations force the removal of healthy enamel and dentin.

Adhesive ceramic onlays have been used as an alternative to minimize the removal of tooth structure. The greatest success with ceramic onlays has been limited to anterior teeth with porcelain veneers,[1,2] whereas they have been used with less success for posterior teeth.[3] This is not surprising as their fracture resistance and abrasiveness are clearly inferior to the gold alloys etchable glass-containing ceramics have replaced in the interest of esthetics.[4] Except for an unnatural appearance, the physical properties of gold alloys have created a standard that has been difficult to match. Gold alloys exhibit toughness, high compressive load-bearing capacity, and low abrasiveness and wear.[4]



Particulate filler composite resins (PFCs) at one time were only considered a treatment option for anterior teeth, but they have been steadily finding wider applications. As the mechanical properties of PFCs have improved, their use has widened to include posterior intracoronal and extracoronal restorations, complete crowns, and fixed partial dentures.[5] Many studies have been under-taken to investigate the filler phases, resin compositions, and curing conditions of the mechanical properties of PFC.[6,7] However, further significant improvements are needed in order to extend the use of PFC to high stress-bearing applications such as direct posterior restorations involving cusps , and indirect inlays and onlay restorations.[7]

Indirect restorations such as inlays and onlays have been used for almost 25 years. They were introduced in the hope of overcoming problems associated with the low degree of conversion related to direct posterior PFCs placed using conventional incremental techniques. The most significant problem was the development of various types of fractures in high stress-bearing areas.[8]

It was hoped the use of the indirect technique would improve the load-bearing capacity of the composite by raising the degree of conversion obtained by laboratory post-curing of the restoration. It is known extra-oral polymerizations of the composite followed by cementation appear to improve marginal fit and minimize contraction stress.[9] Mechanical properties of the composites were also improved by post-cure heat treatment, although such improvements were modest and sometimes not statistically significant.[10,11] The relatively high brittleness and low load-bearing capacity of current PFCs still hinder their use in large stress-bearing restorations.[12-14] Therefore, there is considerable need for improved mechanical properties, especially load-bearing capacity and wear resistance while retaining desirable esthetic properties.

Fiber-reinforced composites (FRCs) have been tested as dental materials, and their use is growing in other dental applications like fixed partial dentures.[15-17] Studies have shown FRCs have superior physical properties over PFCs. Many parameters are known to influence the properties of FRC.[18-22] These include fiber volume fraction, fiber adhesion to the resin matrix, water sorption of resin matrix, and fiber orientation. Although a lot is known about the properties of FRC itself, less information is available on the properties of a material combination of FRC and PFC, especially when used as reinforcement of restorative composite resin. It can be hypothesized when using a FRC substructure for PFC the static load-bearing capacity and flexural properties of the material combination could be improved. Thus, the aim of this study was to determine the static load-bearing capacity and flexural properties of composite resin restorations with two different types of FRC substructures. In addition, the effects of two types of polymerization devices on the properties of the material combinations were tested.

Methods and Materials

The materials used in this study are listed in Table 1. A total of 72 test specimens were prepared to simulate an onlay restoration. The specimens of onlay restoration design were fabricated by placing a 1 mm layer of PFC into the mold as the occlusal surface layer followed by FRC (short random E-glass FRC with fiber length 3 mm or continuous bidirectional E-glass FRC) as the substructure layer at a thickness of 2 and 3 mm. This established the thickness of the restoration to be 4 mm from the cusp tip to the bottom and 3.0 mm from the central fossa to the bottom of the restoration (Figure 1).

Table 1. Materials used in the study.

Brand	Manufacture	Lot no.	Composition
Z250	3M Dental products, St Paul, MN, USA	20040420	Bis-GMA, UDMA****, Bis-EMA *****
Stick	StickTeck Ltd, Turku, Finland	1010321-R-0058	Porous PMMA * pre- impregnated unidirectional E-glass fibers
StickNet	StickTeck Ltd, Turku, Finland	2040315-w-0050	Porous PMMA pre- impregnated bidirectional E-glass fibers
Stick Resin	StickTeck Ltd, Turku, Finland	540 1042	BisGMA**-TEGDMA ***

*PMMA, poly methyl methacrylate, Mw 220.000
**Bis-GMA, bisphenol-A-glycidyl dimethacrylate.
***TEGDMA, triethylenglycoldimethacrylate.
****UDMA, urethane dimethacrylate
*****Bis-EMA, Ethoxylated bisPhenol-A-dimethacrylate

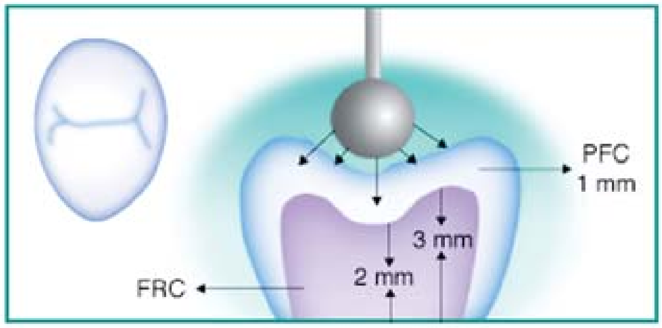


Figure 1. Schematic drawing of onlay-shaped test specimen and the compressive test setup.

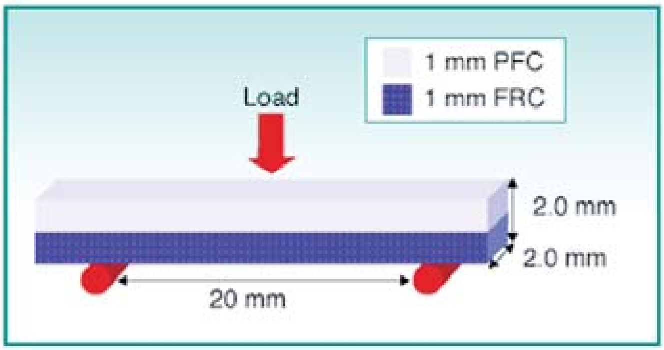


Figure 2. Schematic drawing of bar-shaped test specimen and three-point bending test setup.

The mold for the test specimens was filled and polymerized incrementally either with a hand-light curing unit (LCU) (Optilux –501, Kerr, CT, USA) for 40 s per increment (wavelength: 380 and 520 nm with maximal intensity at 470 nm, light intensity 800 mW/ cm^2) or it was post-cured in a light-curing oven (OLC) (LicuLite, Dentsply, Dreiech, Germany) for 15 min. The specimens from each group (n=6) were either stored dry or stored in water (37°C) for 30 days. The static compressive fracture test was performed using a universal testing machine (Model LRX, Lloyd Instruments Ltd, Fareham, UK) at a speed of 1 mm/min, and data were recorded using PC software (Nexygen Lloyd Instruments Ltd). All specimens were loaded with a steel ball (Ø 3 mm) until fracture, as has been done in previous studies[23] (Figure 1). Fracture patterns of each loaded specimen were visually analyzed and categorized into three typical fracture patterns (compound fracture, delaminating, and splitting).

Bar-shaped test specimens (2 x 2 x 25 mm^3) were prepared using stainless split molds in a brass frame. The specimens were prepared by placing a 1 mm layer of FRC as the substructure, after which and a 1 mm layer of PFC was applied directly on top after polymerization of FRC (Figure 2).

The specimens from each group (n=6) were polymerized either using only a hand-light curing unit for 40 s per increment or post-cured using a light-curing oven for 15 min. The test specimens were loaded with a three-point bending test based on ISO 10477.[24] The setup of the testing machine and recording software were the same as used with the compressive fracture test.

Data of the fracture-load values and flexural properties were statistically analyzed with SPSS (SPSS Inc, Chicago, IL, USA) using analysis of variance (ANOVA). Fiber orientations, storage conditions, and polymerization devices (LCU, OLC) were used as independent factors. Flexural strength ($?_f$) and flexural modulus (E_f) were calculated from the following formulae.[24]

$$?_f = 3F_m l/2bh^2 \qquad E_f = Sl^3/4bh^3$$

Where F_m is the applied load (N) at the highest point of the load-deflection curve, I is the span length (20.0 mm), b is the width of test specimens (mm), and h is the thickness of test specimens (mm). S is the stiffness (N/m) S=F/d, and d is the deflection (mm) corresponding to load F (N) at a point in the straight-line portion of the trace. Toughness was calculated as the integral of the area under the stress/strain curve and reported in units of MPa.

The quantities of fibers in the FRC-containing test specimens were determined by combustion of the polymer matrix of the test specimens for 1 h at 700°C in a furnace (Radiance MSL, Jelrus). Before and after combustion, the weight of the specimens was measured with a balance (Mettler Toledo GmbH) to an accuracy of 0.1 mg. The fiber content, as percentage by volume (Vf) (vol%), was calculated with the following formula.[25]

$$V_f = [(W_f / r_f)/(W_f/ r_f + W_r/ r_r)] \times 100(\%)$$

Where W_f is the weight proportion of E-glass, r_f (=2.54g/cm^3) is the density of E-glass, W_r is the weight proportion of resin, and r_r (=1.238g/cm^3) is the density of resin.[26]

Results

The mean load-bearing capacities of the specimens with standard deviations are given in Table 2. The data showed onlay specimens with a FRC substructure gave higher load-bearing capacity than that obtained with specimens of plain PFC. Onlay specimens polymerized incrementally with the hand-light curing unit only showed higher load-bearing capacity than specimens post-cured in the light-curing oven (Figure 3).

Water storage decreased the load-bearing capacity in all specimens (Figures 4 and 5).

The mean values of the flexural strengths, flexural modulus, and toughness of bar-shaped test specimens are given in Table 3 and Figures 6 and 7.

The data showed specimens post-cured in the light-cured oven had higher flexural strength and modulus than that obtained with specimens polymerized by the hand-light curing unit only. ANOVA revealed all factors significantly affected the fracture load-bearing capacity and flexural properties of material combinations ($p<0.001$), but some interaction between factors existed. The volume quantity of glass fibers (evaluated with combustion) in the specimens with continuous bidirectional fiber substructure was 23 vol% (0.2 SD), and in the specimens with short random fiber substructure 16 vol% (0.7 SD). Fracture patterns were analyzed visually and showed three different types of fracture patterns in all specimens distributed according to the type of fiber orientations (Figure 8):

A. Splitting of two cusps in specimens with only PFC. There was no difference in fracture

Table 2. Mean fracture load values (N), with standard deviations, of onlay-shaped test specimens.

	Group A (LCU)		Group B (OLC)	
Specimens	Dry	Water*	Dry	Water*
	Fracture load (N) (SD)		Fracture load (N) (SD)	
Plain PFC	1413^{b} (419)	744^{a} (197)	626^{a} (193)	566^{a} (177)
PFC with FRC (short random fibers)	2318^{d} (137)	1900^{bcd} (81)	2139^{cd} (192)	1901^{bcd} (270)
PFC with FRC (continuous bidirectional fibers)	2206^{cd} (286)	1983^{bcd} (558)	2014^{bcd} (514)	1666^{bc} (288)

Superscript letters indicate data sets that are not statistically different ($p > 0.05$)
*= water-stored at 37°C for 30 days
LCU= hand-light curing unit
OLC= post-cured in light-curing oven

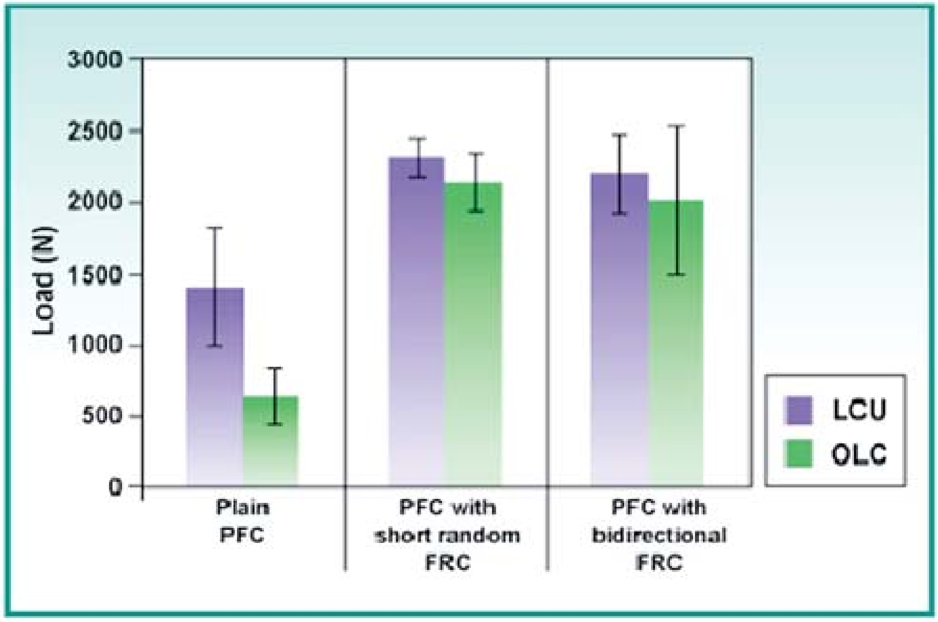


Figure 3. The effect of polymerization type on dry stored test specimens on mean values of load-bearing capacity. LCU = hand-light curing unit, OLC = post-cured in light-curing oven. Vertical lines represent standard deviations.

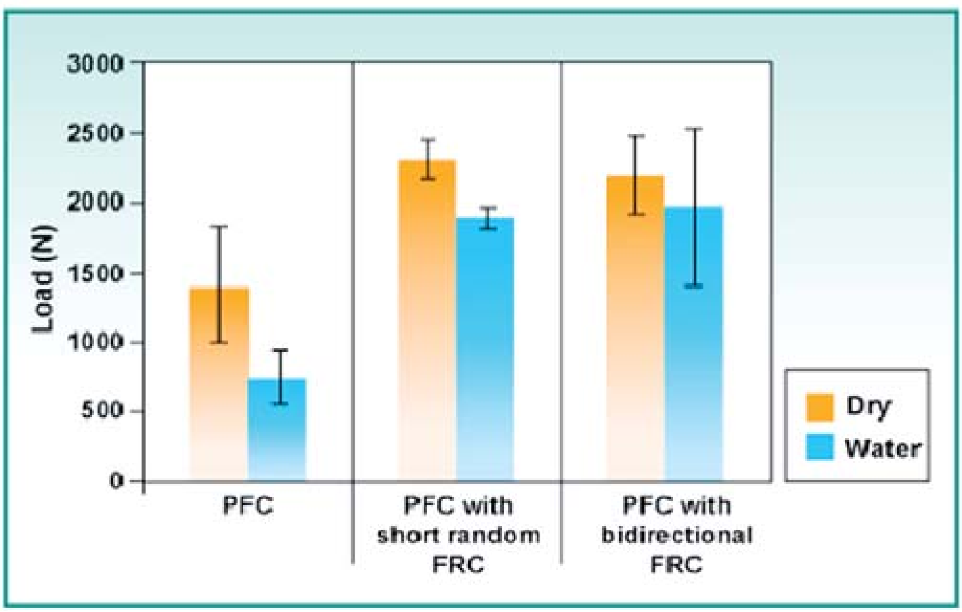


Figure 4. The effect of storing condition on mean values of static load-bearing capacity of test specimens polymerized with hand-light curing unit. Vertical lines represent standard deviations.

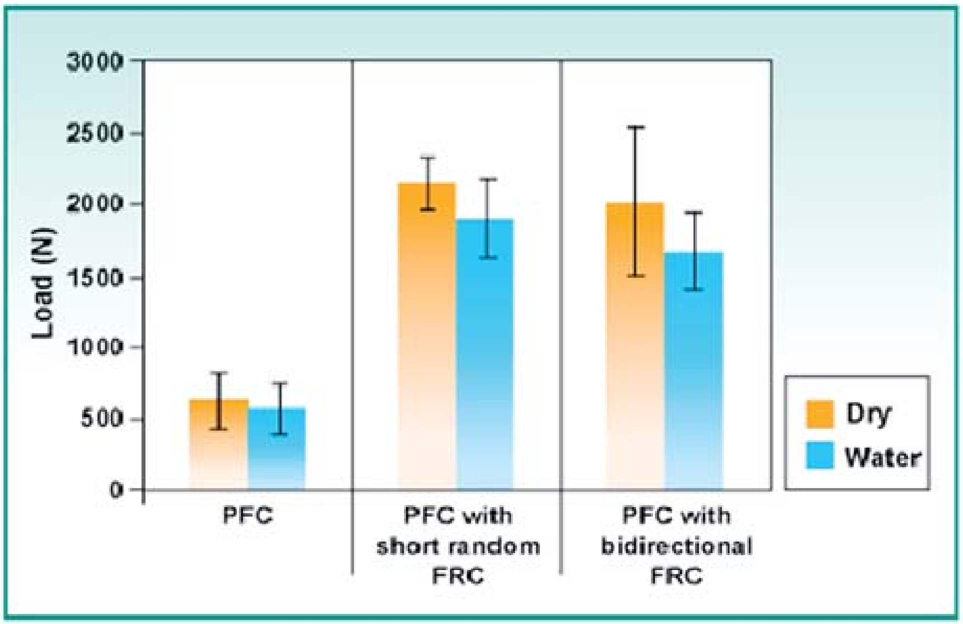


Figure 5. The effect of storing condition on mean values of static load-bearing capacity of test specimens post-cured in light-curing oven. Vertical lines represent standard deviations.

Table 3. Mean results, with standard deviations, of three-point bending test of bar-shaped test specimens.

Specimens	Maximum load (N)		Flexural strength (MPa)		Flexural modulus (GPa)		Toughness (Mpa)	
	LCU	OLC	LCU	OLC	LCU	OLC	LCU	OLC
Plain PFC	23(3)	34(4)	88^{a}(12)	128^{ab}(15)	11.4^{ab}(2)	17^{c}(3.4)	0.103^{a} (.03)	0.098^{a} (.02)
PFC with FRC (short random fiber)	52(23)	64(16)	193^{ab}(85)	240^{b}(61)	8^{a}(2.5)	11.6^{ab}(3)	0.62^{ab}(.3)	0.47^{ab}(.1)
PFC with FRC (continuous bidirectional fiber)	61(9)	68(12)	230^{b}(35)	254^{b}(85)	8^{a}(2)	16^{bc}(2.6)	1.1^{b}(.3)	0.47^{ab}(.2)

Superscript letters indicate data sets that are not statistically different ($p > 0.05$)
LCU= hand-light curing unit.
OLC= post-cured in light-curing oven.

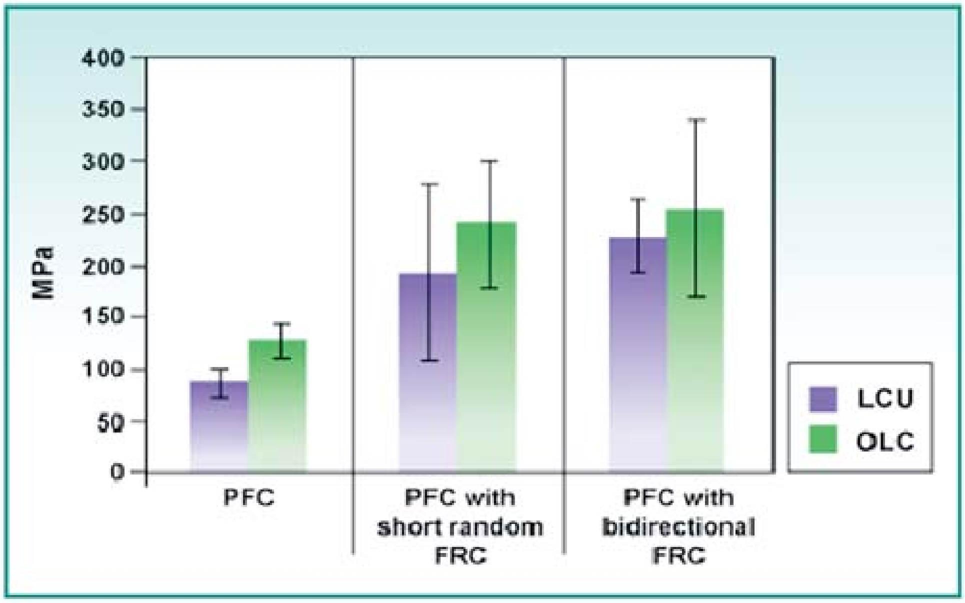


Figure 6. Mean values of flexural strengths of bar-shaped test specimens. LCU = hand-light curing unit, OLC = post-cured in light-curing oven. Vertical lines represent standard deviations.

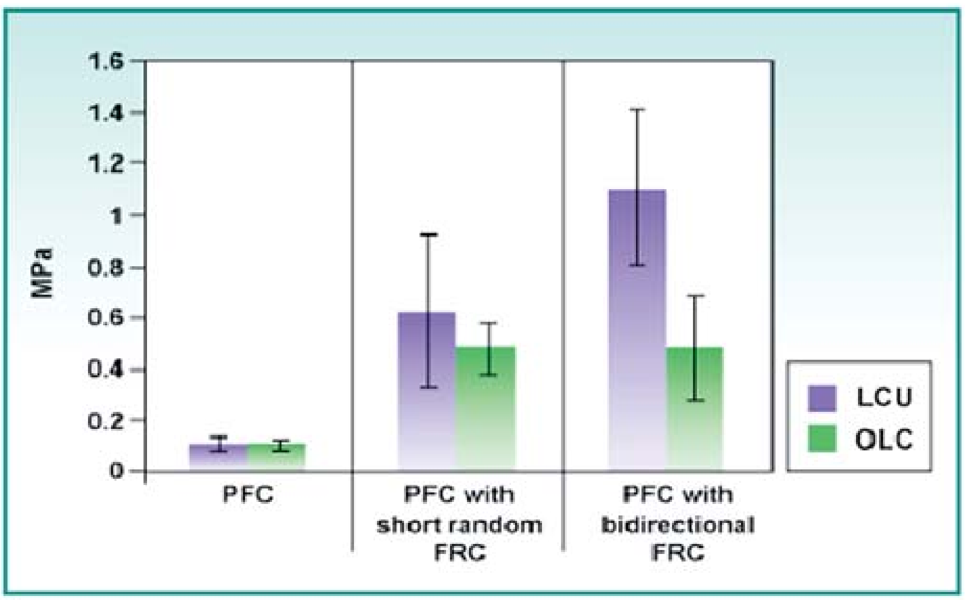


Figure 7. Mean values of toughness of bar-shaped test specimens. LCU = hand-light curing unit, OLC = post-cured in light-curing oven. Vertical lines represent standard deviations.

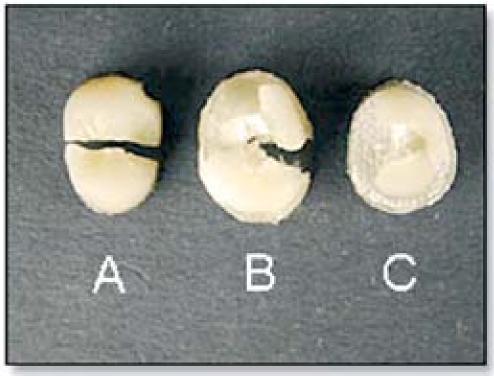
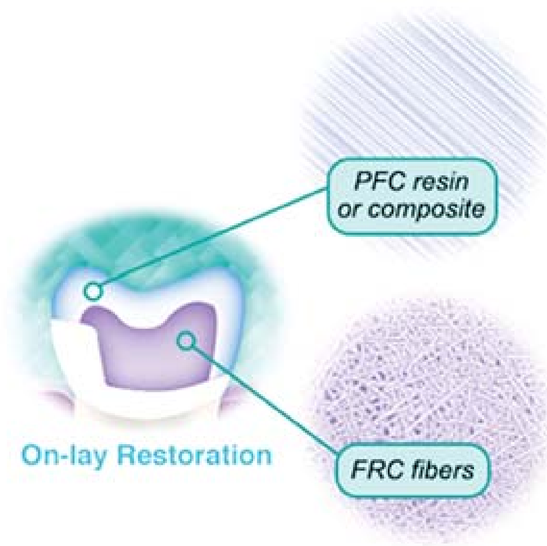


Figure 8. Different types of fracture patterns; A. Splitting, B. Compound fracture, and C. Delaminating.



patterns according to storage condition and polymerization device.

B. Compound fracture of PFC with underlying short random FRC.

C. Delaminating of PFC from underlying continuous bidirectional FRC.

Discussion

After years of follow-up of indirectly or directly made posterior composite restorations, clinical studies showed fracture of the restoration was the most common failure, with no significant differences between the two techniques.[7,28] However, FRCs are a group of materials with high toughness and strength and have been used in many applications such as in prosthodontics and periodontology.[29] Currently, the interest in using FRC is growing and an acceptable success rate in the use of FRC to reinforce long-term restorations like FPDs has been reported.[15,30]

Short random and continuous bidirectional FRCs are used as filler to reinforce resin composite resulting in a modest increase in strength.[31,32] On the other hand, due to handling properties and the anisotropicity of the continuous unidirectional FRC,[17,33] the use of this type of FRC may not be optimal in substructures of restorative composite. However, as a restorative material, unidirectional FRC is the most durable and optimal substructure for replacement of teeth in dental inlay bridges.

Short random and continuous bidirectional FRCs, with isotropic and orthotropic mechanical properties, were selected for this study. It was hypothesized the FRC substructure could reinforce the composite restoration for use in high stress-bearing areas of the dental arch. The data showed substantial improvements in load-bearing capacity and flexural properties when the FRC substructure was used. A two to three times higher load-bearing capacity of specimens was obtained compared to that of plain PFC.

The function of the FRC substructure is assumed to support the PFC layer and serve as a crack prevention layer. In order to provide support for the PFC the structural rigidity of the FRC substructure should be higher than that of the PFC surface layer. The fiber orientation and cross-linking density of the polymer matrix likely play a significant role here.

Visible light at the correct wavelength, sufficient intensity, and sufficient exposure time are essential for adequate polymerization of photo-polymerized composite resins.[34] Laboratory studies have shown additional post-curing resulted in increased physical properties of resin materials.[27] On the other hand, clinical studies after a long evaluation time have shown there is no effect of the additional curing on the longevity and load-bearing capacity of the composite resin.[27] In this study post-curing significantly increased the flexural strength and modulus of composite resin, while the load-bearing capacity and toughness decreased.

Continued light exposure time leads to increased hardness of the PFC[35,36] instead of improving the toughness, which in the present study seems

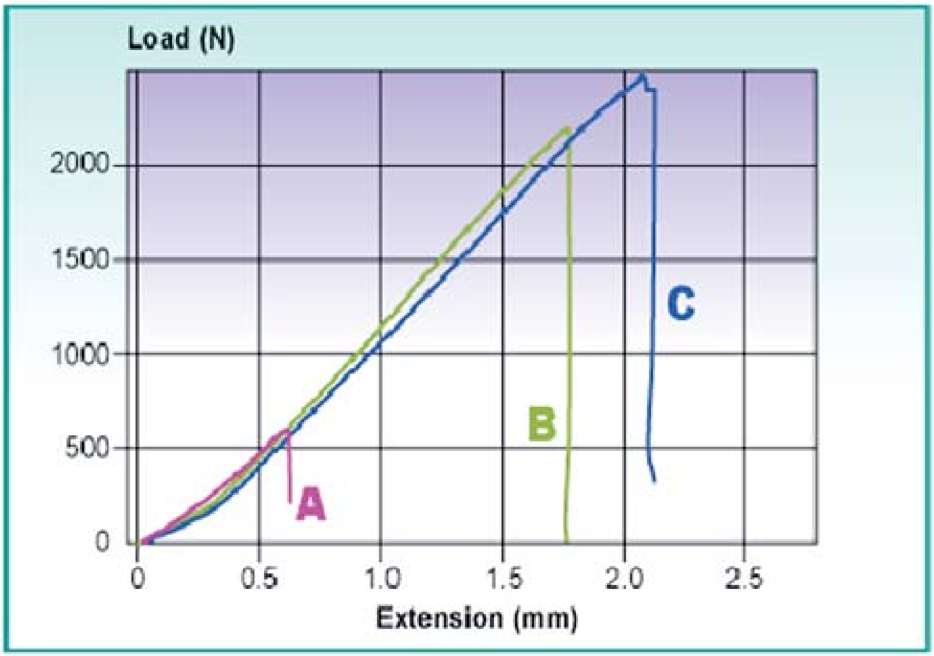


Figure 9. Failure mode in load-deflection curve. **A.** Plain PFC, **B.** PFC with FRC (short random fibers), **C.** PFC with FRC (continuous bidirectional fibers)

to be a key property. The explanation for a higher load-bearing capacity of test specimens polymerized by a hand-light curing unit alone could be related to a lower amount of monomer conversion forming less cross-linked polymer matrix with some residual monomers remaining. The residual monomers plasticizes the polymer matrix, and the lower crosslinking density allows the matrix to flow under high stress, thus, increasing the toughness of the PFC.

The fracture mode was categorized as an instantaneous failure which occurs after a load causes a strain concentration in narrow region sufficient to break the composite structure (Figure 9).

Fracture patterns were analyzed visually, and three types of fracture patterns were found (Figure 8). These occurred according to the type of FRC substructure. Continuous bidirectional FRC has a stiffer structure and likely good ability to slow or arrest crack propagation, which could lead to delaminating of PFC from the underlying FRC.[18] On the other hand, the lower stiffness of short random FRC allowed the crack to propagate through the PFC and FRC, and no delamination was found.

Conclusion

It was concluded by adding a continuous bidirectional or short random FRC substructure under the PFC resin, the load-bearing capacity and flexural properties of material combination were increased. This might have an impact on optimizing the properties of directly and indirectly made composite restorations in high stress-bearing areas.

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