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ORIGINAL ARTICLE

Fiber-reinforced composite substructure: Load-bearing capacity of an onlay restoration

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Abstract

Objective. 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. ***Material and Methods.*** Specimens were prepared to simulate an onlay restoration, composed of a 2 to 3 mm FRC layer as the substructure (short random and continuous bidirectional fiber orientation) and a 1 mm surface layer of PFC. Control specimens were prepared from plain PFC. The specimens were incrementally polymerized with a hand-light curing unit for 40 s and then post-cured in a light-curing oven for 15 min. The specimens were cemented on dentin substrate of extracted human molars using a standard adhesive resin cementation technique. The specimens ($n = 8$/group) were water stored either for 24 h at room temperature or for 4 weeks at 37°C before they were statically loaded until fracture using a universal testing machine. Failure modes were visually examined. ***Results.*** ANOVA revealed that all specimens with FRC substructures had higher values of static load-bearing capacity than those obtained with plain PFC ($p < 0.001$). The load-bearing capacity of all the specimens decreased after water storage ($p < 0.001$). ***Conclusions.*** Restorations made from a combination of FRC and PFC showed better load-bearing capacity than those obtained with PFC alone.

Key Words: *Fracture resistance, posterior composite restorations*

Introduction

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

Adhesively cemented ceramic onlays have been used as an alternative in order to minimize the removal of tooth structure. The greatest success using 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 that of gold alloys. Even so, glass-containing ceramics have been widely used in the name of esthetics [4]. Despite their less than esthetic appearance, the physical properties of gold alloys have created a standard that has been difficult to match; for example, toughness and a high compressive load-bearing capacity [4].

Particulate filler composite resin (PFC), at one time considered only as a treatment option for anterior teeth, has steadily been found to have wider applications. With the improvements in the mechanical properties of PFCs, their use has been widened not only to the posterior intra-coronal area, but also to extra-coronal restorations, and even complete crowns and fixed partial dentures [5]. Many studies have been undertaken to investigate the filler phases, resin compositions, and curing conditions to improve 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 restoration, inlays and onlays [7]. In terms of indirect restorations, inlays/onlays have been used for almost 25 years. They were introduced in the hope of overcoming problems associated with the lower degree of conversion related to

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direct posterior PFCs being placed using conventional incremental techniques. The most common problems that occurred were various types of fractures in high stress-bearing areas [8]. It was hoped that 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 reported that extra-oral polymerizations of the composite followed by cementation appear to improve the marginal fit and minimize contraction stress [9]. The 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]. It therefore follows that there is a considerable need for improved mechanical properties, especially load-bearing capacity and wear resistance, whilst still retaining esthetic properties.

Fiber-reinforced composites (FRCs) have been tested as dental materials and their use is growing in many dental applications, such as in fixed partial dentures [15–17]. Studies have shown FRCs to 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 the resin matrix, and fiber orientation. Although a great deal 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 that by using a FRC substructure under PFC, the static load-bearing capacity of the material combination could be improved. Thus, the aim of this study was to determine the static load-bearing capacity of composite resin restorations with two different types of FRC substructures.

Material and methods

The materials used in this study are listed in Table I.

Specimen preparation

A total of 48 test specimens were prepared to simulate indirect onlay restorations. The specimens of onlay restoration design were made by placing a 1-mm layer of PFC into a silicone mold as the occlusal surface layer, followed by FRC (pre-impregnated short random E-glass FRC having a fiber length of 2–3 mm, or continuous bidirectional E-glass FRC was further impregnated with resin for 15 min before application) as the substructure layer at thicknesses of 2 and 3 mm, where the thickness of the restoration was 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). The control specimens were prepared from plain PFC. The mold for the test specimens was filled and polymerized incrementally (two layers) with a hand-light curing unit (LCU) (Optilux-501; Kerr, Conn., USA) for 40 s per increment (wavelengths: 380 and 520 nm with maximal intensity at 470 nm, light intensity 800 mW/cm^2), then further post-cured in a light-curing oven (OLC) (LicuLite; Dentsply, Dreiech, Germany) for 15 min.

Teeth preparation

Forty-eight extracted, sound, and caries-free human molar teeth of similar occlusal size were selected. Upon collection, adhering soft tissues and blood were removed under running water and the teeth were frozen in wet gauze for a period not exceeding 3 months. The teeth were mounted on an acrylic block (diameter 2.5 cm) at the cement-enamel junction using auto-polymerized acrylic resin (Palapress; Heraus Kulzer, Wehrheim, Germany). Flat superficial dentin surfaces were created by grinding the occlusal surface until all enamel islands disappeared using 1000-grit (FEPA) silicon carbide abrasive paper (Struers, Copenhagen, Denmark) at 300 rpm under water

Table I. Materials used in the study

Brand	Manufacturer	Lot no.	Composition
Z250	3M ESPE Dental products, St Paul, Minn., 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***
RelyX ARC	3M ESPE Dental products, St Paul, Minn., USA	20050309	BisGMA, TEGDMA, Silane-treated ceramic and silica, functionalized

Information provided by the manufacturers.
*PMMA = polymethyl methacrylate, Mw 220.000; **Bis-GMA = bisphenol-A-glycidyl dimethacrylate; ***TEGDMA = triethylenglycol-dimethacrylate; ****UDMA = urethane dimethacrylate; *****Bis-EMA = ethoxylated bisPhenol-A-dimethacrylate.

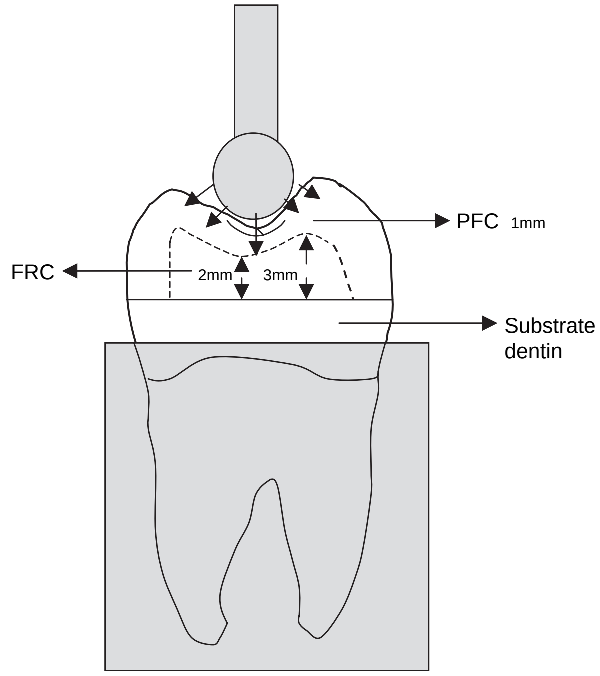

Figure 1. Schematic drawing of onlay-shaped test specimen and the compressive load test setup. PFC = particulate filler composite; FRC = fiber-reinforced composite.

cooling using an automatic grinding machine (Struers Rotopol-11) according to ISO/TR standard 11405 [23]. Teeth that showed any visible pulp exposures or cracks were excluded from the study. The onlay specimens from each group ($n = 8$) were cemented on a dentin substrate using a standard adhesive resin cementation technique, in accordance with the instructions of the manufacturer (phosphoric acid etching for 15 s, water sprayed and dried, then applied primer + adhesive bonding resin (Multipurpose, 3M-Espe),10 s light-cured).

After cementation, the specimens were water stored either for 24 h at room temperature or for 4 weeks at 37°C before they were statically loaded 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). All specimens were loaded until fracture with a steel ball (Ø 3.0 mm), which had been used in previous studies [24–26] (Figure 1).

Catastrophic fracture patterns of each loaded specimen were visually analyzed and categorized into three typical fracture patterns (compound fracture, delaminating, and splitting) (Figure 2)

Data of the fracture-load values were statistically analyzed with SPSS version 10.0 (SPSS Inc., Chicago, Ill., USA) using analysis of variance (ANOVA) followed by the Turkey *post hoc* test at a significance level of 0.05. Fiber orientations and storage conditions were used as independent factors.

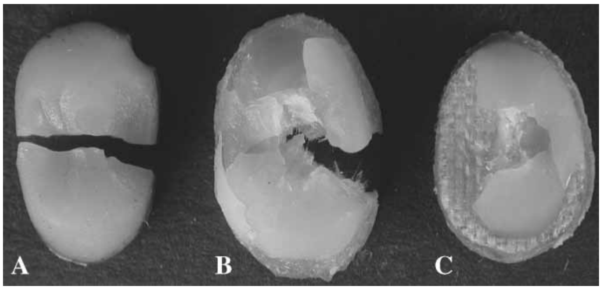

Figure 2. Different types of fracture patterns; A. splitting; B. compound fracture; and C. delaminating.

Results

The mean load-bearing capacities of the specimens with standard deviations (SD) are summarized in Table II. The data show that onlay specimens with FRC substructures had a higher load-bearing capacity than that obtained with specimens of plain PFC ($p < 0.001$). The highest load-bearing capacity was obtained with specimens made from a continuous bidirectional FRC substructure. Water storage decreased the load-bearing capacity in all specimens ($p < 0.001$). ANOVA revealed that all factors significantly affected the fracture load-bearing capacity ($p < 0.001$).

Fracture patterns were analyzed visually and categorized into three different types of fracture patterns; each different fracture pattern occurred according to the type of fiber orientations summarized in Figure 2. Delaminating fracture of PFC occurred when the underlying structure was a continuous bidirectional FRC. Compound fracture occurred in a group having a substructure of short random FRC. The splitting type of fracture occurred between two cusps when the specimen was built with PFC only. There was no difference in fracture patterns in relation to storage conditions.

Discussion

In our study we examined the fracture resistance of specimens simulating posterior composite an onlay under *in vitro* conditions. After years of follow-up of

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

Group	24-h water	30-d water
Plain PFC	1117 (137)^{a}	861 (270)^{a}
PFC with FRC (short random fibers)	1935 (216)^{bc}	1700 (115)^{b}
PFC with FRC (continuous bidirectional fibers)	2393 (104)^{d}	2103 (198)^{cd}

PFC = Particulate filler composite; FRC = fiber-reinforced composite.

24-h water = water stored at room temperature for 24 h.

30-d water = water stored at 37°C for 30 days.

Superscript letters indicate data sets that are not statistically different ($p > 0.05$).

indirectly or directly made posterior composite restorations, the clinical studies show that fracture of the restoration is the most common reason for failure, with no significant differences between the two techniques [27,28]. On the other hand, FRCs from a group of materials with a high degree of toughness and strength were the area of interest in this study. Currently, there is increasing interest in FRC and an acceptable success rate in the use of FRC to reinforce long-term restorations, such as fixed partial dentures (FPDs), has been reported [15,29]. However, fracture or delaminating of veneering composite, wearing and fiber exposure have all been reported [29]. It was hypothesized that a FRC substructure could reinforce the composite in onlay restoration for use in high stress-bearing areas of the dental arch. The data showed substantial improvements in load-bearing capacity when the FRC substructure was used. A two to three times higher load-bearing capacity of specimens was obtained compared to that of PFC alone. The function of the FRC substructure is assumed to be based on its providing support of the PFC layer and its behavior as a crack-stopping layer. To provide support from the FRC to 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 are likely to play a significant role.

Short random and continuous bidirectional FRCs with isotropic and orthotropic mechanical properties were selected for this study. On the other hand, because of handling properties and the anisotropicity of the continuous unidirectional FRC [17,30], the use of this type of FRC may not be optimal in substructures of restorative composite, although as a material, unidirectional FRC is the most durable and optimal substructure for replacement of teeth in dental inlay bridges.

In this *in vitro* study, axial forces were applied to the center of the occlusal surface. Clinically, axial forces in addition to lateral forces and fatigue loading should be considered. Moreover, aging processes, such as alternate thermal stress, mechanical stress, and wear should also be taken into consideration. Stress applied to the teeth and dental restorations is generally low and repetitive rather than being isolated or of impact type. Because of correlation between the fatigue and static loading, the compressive static test was used in the present study [25]. Another aspect that may lead to different fracture resistance values is the type of cementation and material used. However, for this study the cementation was standardized for all specimens. The reinforcing effect requires adequate bonding of the PFC to FRC and optimal thickness of PFC on the FRC. This has been shown in previous studies [24,31,32]. In the materials used in this study, the interfacial bonding of PFC to FRC was based on interdiffusion bonding, in which the monomers of cement penetrate the non-cross-linked phases of the polymer matrix of FRC. In polymerization, semi-IPN (interpenetrating polymer network) bonding was obtained [33,34]. In the case of fully cross-linked polymer matrix of FRC, such semi-IPN bonding cannot be obtained.

The fracture resistance values determined by the various investigators were recorded under different measurement criteria. These criteria were either initial cracking that was interpreted as crack development or a reduction in the load by an absolute or relative amount [35]. For this study, the maximum force on the final fracture was determined. Catastrophic fracture patterns were analyzed visually and three types of fracture patterns were found, where each fracture type occurred according to the type of FRC substructure. Continuous bidirectional FRC gave a stiffer structure and thus the ability to slow or arrest crack propagation, which led to delamination of PFR from the underlying FRC [18]. In contrast, the less stiff structure of short random FRC allowed the crack to propagate through the PFC and FRC to make a compound-like fracture with no delamination found. Because of the brittleness of composite resin, the splitting of two cusps was found in all specimens made from PFC only.

The results of this study are in agreement with previous laboratory studies, which concluded that by using a FRC substructure under the particulate filler composite resin, the load-bearing capacity of the material combination was increased [24–26,36].

However, it should be emphasized that the use of an FRC substructure with a composite occlusal surface is not a substitute for restorations made of gold or ceramics. The results of this study suggest that FRC substructures may offer an alternative towards overcoming some potential problems of composite restoration in high stress-bearing areas.

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