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Continuous-fiber preform reinforcement of dental resin composite restorations

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Abstract

Objectives. Direct-filling resin composites are used in relatively small restorations and are not recommended for large restorations with severe occlusal-stresses. The aim of this study was to reinforce composites with fiber preforms, and to investigate the effects of layer thickness and configurations on composite properties. It was hypothesized that fiber preforms would significantly increase the composite's flexural strength, work-of-fracture (toughness) and elastic modulus.

Methods. Glass fibers were silanized, impregnated with a resin, cured, and cut to form inserts for tooth cavity restorations. Also fabricated were three groups of specimens of 2 mm × 2 mm × 25 mm: a fiber preform rod in the center of a hybrid composite; a thin fiber layer on the tensile side of the specimens; and a thin fiber layer sandwiched in between layers of a hybrid composite. These specimens were tested in three-point flexure to measure strength, work-of-fracture and modulus. Optical and scanning electron microscopy were used to examine the restorations and the fiber distributions.

Results. Microscopic examinations of insert-filled tooth cavities showed that the fibers were relatively uniform in distribution within the preform, and the inserts were well bonded with the surrounding hybrid composite. Specimens consisting of a fiber preform rod in the center of a hybrid composite had a flexural strength (mean (SD); $n = 6$) of 313 (19) MPa, significantly higher than 120 (16) MPa of the hybrid composite without fibers (Tukey's at family confidence of 0.95). The work-of-fracture was increased by nearly seven times, and the modulus was doubled, due to fiber preform reinforcement. Similar improvements were obtained for the other two groups of specimens.

Significance. Substantial improvements in flexural strength, toughness and stiffness were achieved for dental resin composites reinforced with fiber preforms. The method of embedding a fiber preform insert imparts superior reinforcement to restorations and should improve the performance of direct-filling resin composites in large restorations with high occlusal-loads.

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Keywords: Dental restorations; Fiber; Insert; Preform; Resin composite; Strength; Toughness

1. Introduction

Dental resin composites are composed of fillers in an acrylic monomer matrix that is subsequently polymerized to form a solid. These composites are finding increased use in tooth cavity restorations [1–5]. The size and volume fraction of filler particles, the resin composition, the filler–matrix interfacial bonding, and the polymerization conditions have all been shown to influence the composite properties [1–8]. The composite fillers are usually composed of particulate silicate glasses. Mixing filler particles of different sizes to achieve bimodal distributions and higher filler levels can enhance composite properties such as strength, modulus and wear resistance [2–8]. Heat-curing and post-cure heat treatment of resin composites increase the degree of conversion and in turn the composite strength [9–13]. Short fibers [14] and networked fibers [15] have also been used to reinforce resin composites, resulting in modest increases in composite strength. Recently, silica-modified ceramic whiskers have been used to reinforce dental resin composites [16].

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The microstructural improvements in filler treatments, resin compositions and cure conditions have resulted in significant enhancement in the wear resistance of composites [17–19]. Even with these improvements, resin composites are still brittle with relatively low-strength values, rendering them useful only in relatively small restorations [20–22]. For example, even when cured with heat and pressure, a resin composite was considered adequate for use in inlays, but not in crowns due to brittleness [20]. Analysis of crack propagation in dental restorations confirmed scanning electron microscopic observations that resin composite restorations, although exhibiting low-wear rates, were prone to fracture with crack propagation rates higher than those of porcelain [23]. Clinical observations coupled with finite element analysis showed that, during mastication, the inner side of the restoration could be subjected to tensile stress concentrations that lead to fracture initiation [24]. Polymeric materials, while being significantly improved, have still not achieved the strength and toughness of metals to resist these tensile stresses [25]. Even the improved posterior composites were only recommended for relatively small restorations; none of the resin composites were considered acceptable for unrestricted use [21]. This was consistent with a recent clinical study on a resin composite showing that for low-stress premolar restorations, the clinical failure rate at 7 years was relatively low; however, for stress-bearing molar restorations, nearly half of the restorations had failed [22].

Reinforcement with fibers was shown to impart strength and toughness to a number of dental materials [26–35]. The term continuous fibers was used to describe fibers that were either aligned or in mesh or other forms, and that extended continuously through a major portion of the composite specimen [28,29,31–36]. Continuous fibers were differentiated from chopped fibers [14] and whiskers [16] in that chopped fibers and whiskers were discontinuously distributed in the matrix, and that each fiber or whisker was much shorter than the dimensions of the composite specimen. Continuous fibers were used in the reinforcement of denture base resins, bridges, splints, retainers, orthodontic arch wires, fixed prosthodontic appliances and fixed partial dentures [26–35]. However, continuous fibers have not been used for the reinforcement of direct-filling tooth cavity restorations.

The objectives of the present study were to use continuous fiber preforms to reinforce direct-filling resin composites, and to investigate the effects of layer thickness ratios and configurations on composite properties. It was hypothesized that the fiber preforms would significantly increase the flexural strength, work-of-fracture (toughness) and elastic modulus (stiffness) of the reinforced composite. In the fiber preform method, continuous fibers were incorporated into a dental resin and cured to form fiber preforms, or inserts, which were then placed into prepared tooth cavities. The rest of the tooth cavity was filled with a conventional resin composite. This resulted in restorations with substantially higher flexural strength, toughness and modulus, rendering them more resistant to deformation and fracture. One reason for using fiber preform inserts with resin composite veneer, instead of filling fibers throughout the restoration, was to avoid surface problems such as fiber pullout during polishing and wear. Another reason for the use of fiber preforms was to reduce polymerization shrinkage, because part of the restoration (the fiber preform) was cured prior to placement into the tooth cavity. In addition, the matrix of the preform contained pre-cured glass ionomer particles for fluoride release.

2. Materials and methods

2.1. Paste of dental resin and pre-cured glass ionomer powder

The powder and liquid components of a conventional glass ionomer (Ketac™-Bond, ESPE, Germany)[2] were mixed according to the manufacture's instructions, and placed into steel molds of dimensions of 2 mm × 2 mm × 25 mm. The open sides of the mold were covered with mylar strips, mechanically clamped between two glass slides, and the entire assembly was incubated in a humidor at 100% relative humidity at 37 °C for 24 h. As detailed in a previous study [37], the hardened specimens were demolded and manually ground in a mortar with a pestle into a fine powder of a particle size ranging from approximately 0.5 to 5 μm, with a mean diameter of approximately 1 μm. This cured, ground glass ionomer cement powder will be referred to as pre-cured glass ionomer powder. This powder was silanized by mixing it with mass fractions of 2% *n*-propylamine (Aldrich, Milwaukee, WI) and 4% 3-methacryloxypropyltrimethoxysilane (MPTMS) in cyclohexane by means of a rotary evaporator at room temperature for 30 min and then at 90 °C under a moderate vacuum until dry [37]. The silanized, pre-cured glass ionomer powder was mixed with a resin of *Bis*-GMA and triethylene glycol dimethacrylate (TEGDMA) at 1:1 mass ratio, photo-activated with mass fractions of 0.2% camphorquinone and 0.8% ethyl 4-*N*,*N*-dimethylaminobenzoate. The filler level of glass ionomer powder in the resin was 20% mass fraction to provide a moderate fluoride release [37], while producing a paste sufficiently flowable for impregnation into the fiber bundles, as described in Section 2.2.

2.2. Fiber preform inserts

E-glass fibers (Owens Corning Fiberglass, Columbus, OH) were used in the present study due to their translucency

[2] Certain commercial materials and equipment are identified in this paper to specify the experimental procedure. In no instance does such identification imply recommendation or endorsement by the National Institute of Standards and Technology or the ADA Health Foundation or that the material or equipment identified is necessarily the best available for the purpose.

and ease of silanization and bonding to the dental resin. The fiber diameter was measured (mean ± one standard deviation, or SD; $n = 6$) with scanning electron microscopy (SEM, model JSM-5300, JEOL, Inc., Peabody, MA) to be 16 (2) μm in a previous study [38], and the fiber tensile strength was measured in uniaxial tension to be 2.6 (1.2) GPa. According to the manufacturer, the elastic modulus of the fiber is 69 GPa, and the density is 2.55 g/cm^3. The fibers were silanized by immersing fiber bundles of approximately 60 mm in length in cyclohexane with mass fractions of 2% *n*-propylamine and 4% 3-MPTMS under moderate vacuum until dry. The silanized fiber bundle was inserted into a transparent glass tube of an inner diameter of approximately 1.3 mm to produce a fiber volume fraction of 50%, as calculated by density and weight. The above-described resin containing 20% mass fraction of glass ionomer powder was filled into a syringe and then manually injected into the glass tube. The resin was flowable enough to wet and impregnate the fibers according to preliminary studies. The fiber volume fraction of 50% was selected because the resin impregnation became more difficult at higher volume fractions, while the fiber distribution was less uniform at low-volume fractions. The composite paste in the tube was cured using visible light (Triad 2000, Dentsply International, Inc., York, PA) for 1 min. The glass tube was subsequently broken and the hardened fiber composite rod was cut with a sharp surgical blade into rods of two different lengths of approximately 8 or 25 mm; the diameter was approximately 1.3 mm. These rods will be referred as fiber inserts or fiber preforms. The 25 mm rods were used to make flexural specimens; the 8 mm rods were chosen to be suitable for the type of tooth cavity restorations described in Section 2.3.

2.3. Tooth cavity restorations

The fiber inserts were used to reinforce large posterior MOD (mesial–occlusal–distal) restorations in extracted human molars. A cavity of approximately 9 mm in length and 2.5 mm in width was prepared in six extracted, similarly sized human third molars. The depth of the cavity ranged from about 1.5 to 2 mm. An adhesive resin (OptiBond™, Kerr Corp., Orange, CA) was brushed onto the cavity walls and cured with visible light (Elipar Highlight™, ESPE, Germany) for 30 s. A fiber insert was placed into the cavity and oriented mesial-distally. The rest of the cavity was then filled with a hybrid resin composite (TPH™, Caulk/Dentsply, Milford, DE) and cured with visible light (Elipar Highlight™) for 1 min. TPH™ consists of silanized silicate filler particles about 0.8 μm in diameter and a filler mass fraction of 78% in a matrix–resin of a urethane-modified *Bis*-GMA and TEGDMA. The restored teeth were immersed in distilled water at 37 °C for 24 h. They were then sectioned with a diamond blade axially from buccal to lingual. The sectioned halves were embedded in epoxy and polished sequentially with diamond pastes of 15, 6, 3 and 1 μm for microscopic examination of fiber distribution and bonding between the fiber insert and the hybrid composite.

2.4. Fabrication of specimens

Three groups of flexural specimens of 2 mm × 2 mm × 25 mm were fabricated to measure the flexural strength, elastic modulus and work-of-fracture. The first group of specimens contained the fiber preform rods of 25 mm in length and 1.3 mm in diameter. A layer of a hybrid composite (TPH™) of approximately 0.35 mm thick (as measured by mass) was first placed into the mold and cured with visible light (Triad 2000, Dentsply International, Inc., York, PA) for 1 min. The fiber preform rod was then placed on top of the hybrid composite in the center of the mold, and the rest of the mold was filled with the same hybrid composite and light cured for 1 min to form a cohesive specimen. In addition, specimens with fibers throughout were also fabricated by placing the silanized glass fibers (25 mm in length) with the same flowable resin paste containing a mass fraction of 20% glass ionomer particles into the mold to fill the entire mold, and curing the mixture with visible light (Triad 2000) for 1 min on each of the two open sides of the specimen. The amount of fibers and resin were weighed to yield a fiber volume fraction of approximately 50% as calculated using the density values. Specimens of the hybrid composite (TPH™) without fibers were also made in the same molds using the same curing method.

Specimens of the second group consisted of a thin fiber layer supporting a thick hybrid composite, and were tested with the fiber layer in tension to simulate the cases in which the inner side of the restoration was in maximum tension [22]. The total specimen thickness was approximately 2 mm. The hybrid composite (TPH™) layer thickness (L_H) to fiber composite layer thickness (L_F) ratios, L_H/L_F, were: 2 mm/0 mm (hybrid control), 1.8 mm/0.2 mm, 1.6 mm/0.4 mm, and 0 mm/2 mm (fiber composite control). In making the specimens, the fibers were first cut to a length of approximately 25 mm and silanized as described in Section 2.2. The amounts of fibers and resin (containing 20% mass fraction glass ionomer particles) were weighed to yield the above thicknesses of fiber preforms. The fiber to resin ratio yielded preforms with a fiber volume fraction of approximately 50% as calculated using the density values. The mixture of resin and fibers in the 2 mm × 2 mm × 25 mm mold was cured using visible light (Triad 2000) for 1 min to form a fiber preform. To make the layered specimens, a fiber preform was first placed into the molds and a hybrid composite (TPH™) was then placed on top of the fiber preform to fill the rest of the mold. The specimen was light cured (Triad 2000) for 1 min on each of the two open sides to form a cohesive solid specimen. Six specimens were made at each of the four L_F/L_H ratios for a total of 24 specimens.

The third group of specimens had a sandwich structure: hybrid composite/fiber preform/hybrid composite.

The hybrid composite on one side of the fiber preform had a thickness of approximately 0.2 mm and served as a veneer layer. Twelve fiber preforms, six each at thicknesses of 0.4 and 0.8 mm, were made following the procedures described above. Correspondingly, the hybrid composite on the other side of the fiber preform had thicknesses of 1.4 and 1.0 mm, respectively, for a total specimen thickness of approximately 2 mm. Each specimen had TPH™ paste on both sides of the fiber preform and was cured using visible light (Triad 2000) for 1 min on each of the two open sides to form a cohesive composite specimen. In flexural testing, the thin veneer layer was placed in tension.

2.5. Testing

A standard three-point flexural test [39] with a span of 10 mm was used to fracture the specimens at a cross-head speed of 1 mm/min on a computer-controlled Universal Testing Machine (model 5500R, Instron Corp., MA). The following properties were evaluated: flexural strength, elastic modulus, and work-of-fracture (the energy required to fracture the specimen, obtained from the area under the load-displacement curve divided by the specimen's cross-section area) [36–38].

The polished sections of fiber preforms and tooth restoration were viewed in an optical microscope with Nomarski interference contrast (Nikon Diaphot, Mager Scientific, MI) coupled with a video micrometer (model 305, Colorado Video, CO) to examine fiber distribution and bonding between the fiber insert and the hybrid composite, and to measure the fiber volume fraction. Scanning electron microscopy (SEM, model JSM-5300, JEOL, Peabody, MA) was used to examine the microstructure of fiber preforms such as fiber–resin bonding and the distribution of the pre-cured glass ionomer particles.

One standard deviation is given for comparative purposes in this paper as the estimated standard uncertainty of the measurements. These values should not be compared with data obtained in other laboratories under different conditions. One-way ANOVA was performed to detect significant ($\alpha = 0.05$) effects of structure on mechanical properties. Tukey's Multiple Comparison procedures were used to compare the measured values at a family confidence coefficient of 0.95.

3. Results

Fig. 1(A) is an optical micrograph showing a typical cross-section of an MOD restoration in a human third molar. The fiber preform insert was surrounded by the hybrid composite (TPH™) above the dentin and below the occlusal-surface. The fiber preform insert was approximately 8 mm in length in a cavity of about 9 mm, and the section was cut nearly perpendicular to the fiber axis. The fiber preform appeared to be firmly bonded to the hybrid composite without gaps between the two (Fig. 1(A)), as verified with SEM at higher magnifications up to 10,000. The fibers appeared relatively uniformly distributed in most areas of the preform. Several pores were visible both in the fiber preform and in the hybrid composite. Fig. 1(B) shows a high magnification SEM micrograph, where 'F' denotes 'fiber', 'R' denotes the resin matrix of the fiber preform containing a mass fraction of 20% pre-cured glass ionomer particles, and 'G' denotes a glass ionomer particle. The silanized glass fiber appeared to be well bonded with the resin matrix. In making the fiber preforms, the fiber volume fraction was set at 50% which was calculated using the density values. The actual volume fraction was measured on six optical microscope fields by counting the number of

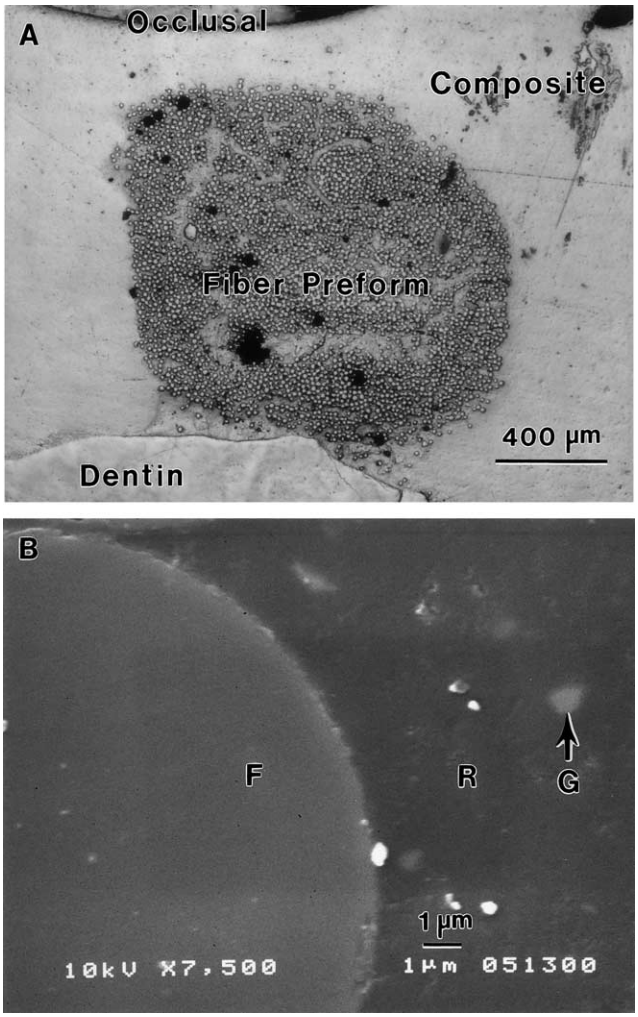

Fig. 1. (A) Optical micrograph of a cross-section of an MOD restoration in a human third molar. The fiber insert was 8 mm in length in a cavity of 9 mm in length, located above the dentin and below the occlusal-surface. The cross-section was made perpendicular to the fiber preform. The insert appeared to be well bonded to the surrounding hybrid composite. The fibers were relatively uniform in distribution within the preform. (B) High magnification SEM, where 'F' denotes 'fiber', 'R' denotes the resin–matrix of the fiber preform containing 20% glass ionomer particles, and 'G' denotes a glass ionomer particle filler in the resin.

fibers inside the field and then dividing the fiber area by the total area of the field. This yielded a fiber volume fraction of 52.2% (8.8%), showing some degree of local variation in fiber distribution.

Fig. 2 plots flexural strength, work-of-fracture and elastic modulus of the first group of specimens consisting of a fiber preform rod in the center of the specimen. Each value is the mean of six measurements with the error bar showing one standard deviation. Horizontal lines indicate values that are not significantly different (Tukey's multiple comparison test; family confidence coefficient = 0.95). The hybrid composite specimens with a fiber preform insert had a flexural strength (mean (SD); $n = 6$) of 313 (19) MPa, significantly higher than 120 (16) MPa of the hybrid composite without a fiber insert (Tukey's multiple comparison test; family confidence coefficient = 0.95). Both of them were significantly lower than 458 (40) MPa of the fiber composite with fibers distributed throughout the specimen. The work-of-fracture and modulus of the specimens containing fiber preform inserts were increased by nearly seven times and two times, respectively, over those without fiber preform inserts.

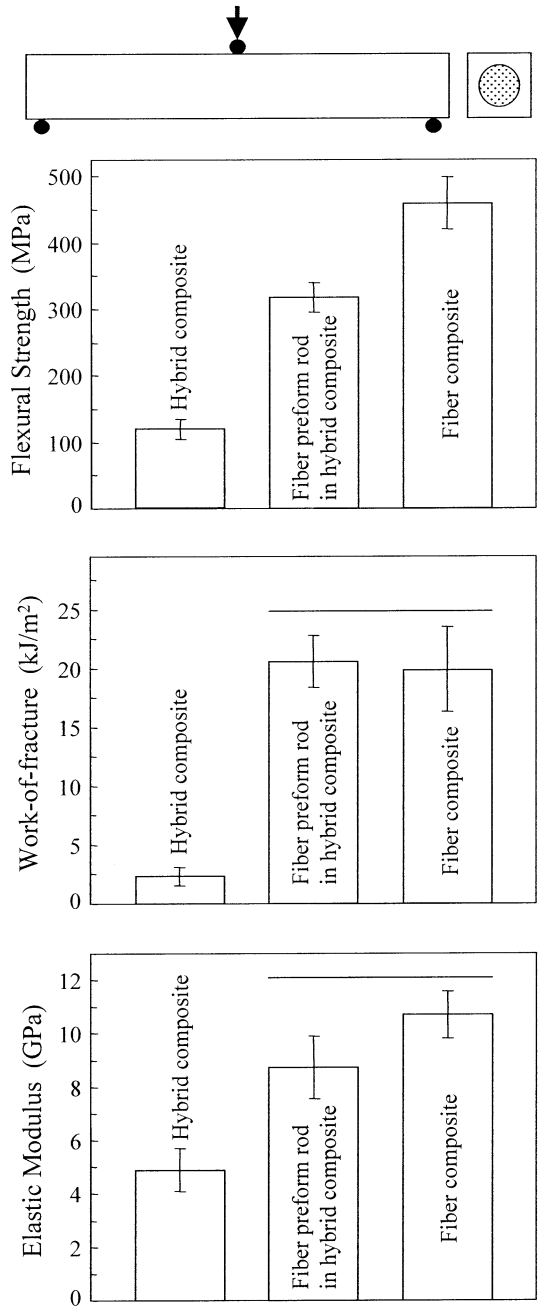

Fig. 2. Plots showing flexural strength, work-of-fracture and modulus of the first group of specimens with a fiber preform rod in the specimen center. Each value is the mean of six measurements with the error bar showing ±one standard deviation. Horizontal lines indicate values that are not significantly different (Tukey's multiple comparison test; family confidence coefficient = 0.95). The strength, work-of-fracture and modulus of the specimens with fiber preform rods were 2.6, 7 and 2 times higher, respectively, than those without fiber preform rods.

The results from the second group of specimens consisting of a thin fiber preform layer on the tensile side are plotted in Fig. 3. The specimens with thin layers of fiber preform at L_H/L_F of 1.8 mm/0.2 mm had a strength (mean (SD); $n = 6$) of 395 (11) MPa, statistically similar to 359 (44) MPa at $L_H/L_F = 1.6$ mm/0.4 mm (Tukey's multiple comparison test; family confidence coefficient = 0.95). Both of them are slightly lower than that of the fiber composite control ($L_H/L_F = 0$ mm/2 mm), but three times higher than that of the hybrid composite control ($L_H/L_F = 2$ mm/0 mm). The work-of-fracture and modulus of the layered specimens containing fiber preforms were not significantly different from each other. As a result of reinforcement with a thin fiber preform layer, the work-of-fracture of the specimens was increased by nearly seven times, and the elastic modulus was doubled.

Fig. 4 shows results from the third group of specimens having a thin fiber preform layer sandwiched in the middle of a hybrid composite, and tested with a thin veneer layer (0.2 mm) of the hybrid composite in tension. The strength (mean (SD); $n = 6$) of specimens with the 0.2 mm/0.4 mm/1.4 mm hybrid/fiber/hybrid configuration was 438 (58) MPa, not significantly different from 442 (43) MPa with the 0.2 mm/0.8 mm/1.0 mm configuration (Tukey's multiple comparison test; family confidence coefficient = 0.95). The work-of-fracture values of these two configurations were also similar, but the moduli were significantly different from each other. Fiber preform reinforcement for the sandwich structures increased the strength by more than three times, work-of-fracture by eight times, and modulus by two times, over the corresponding properties of the same hybrid composite without a fiber preform.

4. Discussion

Substantial improvements in flexural strength, work-of-fracture (toughness) and elastic modulus (stiffness) were achieved in dental resin composites reinforced with fiber

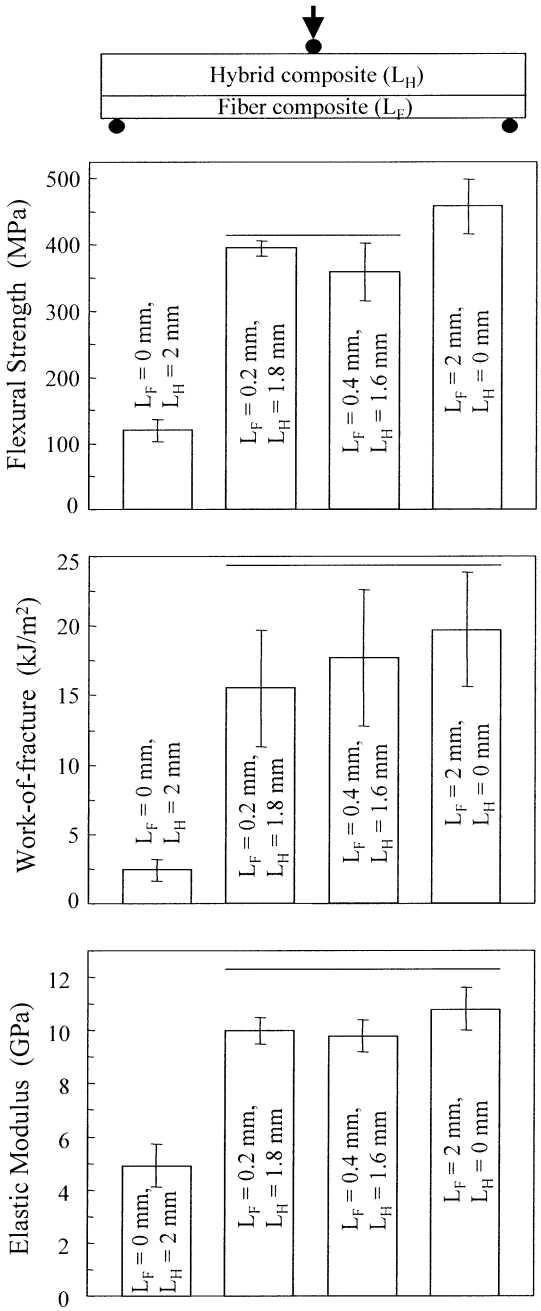

Fig. 3. Flexural strength, work-of-fracture and elastic modulus of the second group of specimens consisting of a thin fiber preform on the tensile side. Horizontal lines indicate values that are not significantly different (Tukey's multiple comparison test; family confidence coefficient = 0.95).

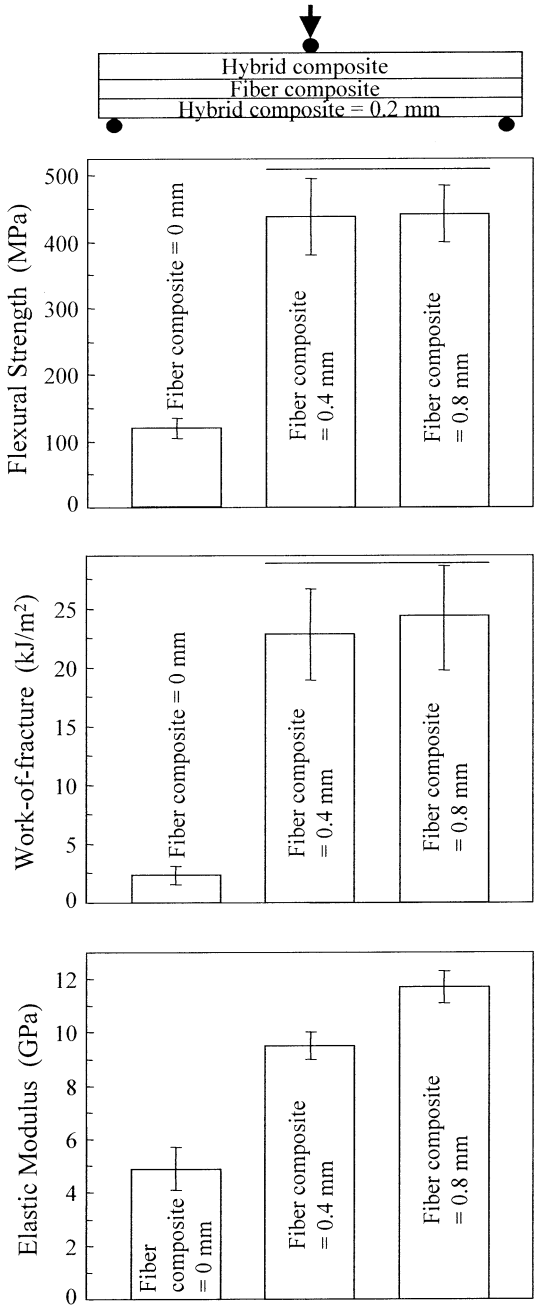

Fig. 4. Flexural strength, work-of-fracture and elastic modulus of the third group of specimens having a thin fiber preform sandwiched in the middle and tested with a thin veneer layer (0.2 mm) of a hybrid composite placed in tension. Horizontal lines indicate values that are not significantly different (Tukey's multiple comparison test; family confidence coefficient = 0.95).

preforms. The strength of composite dental restorative materials is usually considered to be appropriately measured in flexural tests [30–32,34,35,40–43]. The direct measurement of tensile strength is technically difficult, does not reflect the flexural deformation in occlusal-loading situations, and does not allow a selected surface of the specimen to be tested in tension. The compressive strength is only indirectly related, in a complex way, to a combination of tensile and shear failure modes. The measurement of diametral tensile strength requires that the material exhibit no plastic flow, which does not hold true for most dental resin composites. Therefore, the flexural test has been widely used to characterize the mechanical properties of dental restorative materials [30–32,34–38,40–43]. In the present study, the specimens containing fibers throughout the bars had a flexural strength of nearly 450 MPa. This value is compared with previous flexural strengths for fiber-reinforced composites of approximately 565 MPa [28] and

426 MPa [32] at similar fiber volume fractions. The specimens containing fiber preforms with various configurations achieved flexural strengths ranging from more than 300 to 400 MPa, while that of a commercial hybrid composite was 120 MPa. The latter was typical for current dental resin composites. For example, the flexural strengths of a prosthetic composite and an inlay/onlay composite were 123 and 120 MPa, respectively, both measured in our laboratory following the same testing procedures [13]. For comparison, glass ionomer cements generally had flexural strength values of 10–30 MPa, and resin-modified glass ionomers had flexural strength values of 40–60 MPa [37,40]. An experimental composite reinforced with networked fibers had a flexural strength of nearly 140 MPa [15]. Recent studies showed that silica-fused whisker composites had strengths of nearly 200 MPa [16]. The flexural strength values achieved in the present study were two to three times higher than the best values achieved previously, together with multi-fold increases in work-of-fracture and modulus. Such superior reinforcement obtained using the fiber preforms may be useful in extending the resin composites to large restorations in areas that may experience high occlusal-loads.

The present study used glass fibers in a unidirectional orientation to make the fiber preforms. Other types of fibers such as ceramic fibers and polymer fibers with varied volume fractions need to be explored to investigate the effects of fiber type and fiber volume fraction on the preform properties. A previous study screened several types of fibers for dental use [34]. Since the fiber preforms in tooth cavities are covered with an aesthetic composite, the esthetics of the fibers may not be as critical, which may allow the use of stronger fibers that are less aesthetic [38]. Another important future study would be to examine the effects of fiber orientation (e.g. aligned one- or two-dimensionally, randomly mixed, or in mesh or woven forms) on the properties of the preform and the entire restoration. Woven fibers and meshes would be beneficial because they can reinforce the restoration in multiple directions [34,35]. While the present study focused on the use of fiber preforms cured with light in direct-filling restorations, an interesting study would be to characterize the properties of indirect composites reinforced with fiber preforms cured with light, heat or heat/pressure. The application of pressure would likely help reduce the porosity, while heat-curing may increase the degree of conversion and further improve the composite strength [9–13].

In addition to improvements in strength, work-of-fracture and modulus, the fiber preforms contained pre-cured glass ionomer particles for fluoride release [37]. A mass fraction of 20% glass ionomer fillers was used in the present study. Further studies should investigate the effects of different filler levels on the amount of fluoride release as well as mechanical properties of the fiber preforms. Besides pre-cured glass ionomer particles, other fluoride releasing agents could also be incorporated, and other types of fillers could be added into the fiber preforms for esthetics or to improve properties. Another possibility would be to use carboxylic acid–resin mixtures and ion-leachable fluorosilicate glass fillers for fluoride release [44].

Polymerization shrinkage in direct-filling resin composite restorations causes internal stresses and even leakage at the tooth cavity walls [45]. Efforts at reducing such polymerization shrinkage included the modification of resin–matrix compositions, the use of higher filler levels to reduce the amount of polymerizable resin, and the improvement of curing conditions [6–8,46]. Glass–ceramic 'megafiller' inserts were used in composite restorations, one advantage of which was the reduction of the volume of resin and resulting in a decrease in polymerization shrinkage [47]. In the present study, pre-cured fiber composite inserts were incorporated into restorations in order to substantially increase the strength, toughness and elastic modulus. Furthermore, polymerization shrinkage is expected to decrease. For simple illustration, a restoration approximately 2.5 mm wide, 9 mm long and 1.5 mm deep, similar to the ones in the present study, had a volume of approximately 33.8 mm^3. A fiber preform insert with a diameter of approximately 1.3 mm and a length of 8 mm had a volume $= \pi$ (radius)^2 length $= 3.14 \times (1.3\ mm/2)^2 \times 8\ mm = 10.6\ mm^3$. Therefore, about one third of the restoration was pre-cured and would shrink little during the curing of the entire restoration. Further studies are needed to measure the actual reductions in polymerization shrinkage of dental direct-filling restorations reinforced with fiber preform inserts. Further studies should also examine the effects of long-term water aging on fiber preform composites. Previous studies showed that water storage reduced the strength of fiber-reinforced composite by approximately 27% [48,49]. Our on-going study also showed that water aging up to 2 years significantly decreased the flexural strength of a whisker-reinforced resin composite.

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