Model System for Measuring the Effects of Position and Curvature of Fiber Reinforcement Within a Dental Composite

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Keywords
Dental materials; composite resin; fiber; fiber position; fiber orientation; flexural strength; toughness; flexural modulus; laboratory research.

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Abstract

Purpose: The aim of this study was to compare the effect of fiber curvature and position on flexural strength (FS), toughness, and elastic modulus in a dental flowable composite test specimen.
Methods and Materials: Test specimens made of composite resin (Denfil Flow) were reinforced with preimpregnated glass fibers (Interlig). Control specimens (group A) did not contain fiber reinforcement. Fibers were placed with different positions and orientations into the test specimens (2 mm × 2 mm × 25 mm) (groups B, C, D). The test specimens (n = 10) were stored in distilled water for 3 days at 37°C before testing in a three-point loading test (ISO 10477) at a crosshead speed of 1 mm/min to determine FS, flexural modulus (FM), and toughness. Data were analyzed with 1-way analysis of variance and Tukey HSD ($\sigma = 0.05$).
Results: The FM varied from 4.7 ± 0.5 to 6.7 ± 0.5 GPa. The lowest flexural strength and toughness values in reinforced specimens resulted from compression side fiber reinforcement (132 ± 12 MPa, 21 ± 4 MJ) and the highest from curved fiber reinforcement (174 ± 8 MPa, 83 ± 28 MJ), though this was not statistically significant from tension-side reinforcement. Although the toughness of the curved reinforced group was significantly higher than other groups, the flexural strength of curved reinforcement was not significantly higher than tension-side reinforcement.
Conclusion: Position and fiber orientation influenced the flexural strength, FM, and toughness. The most effective in increasing toughness was curved placement of fibers.

Use of fiber and composite combinations has increased dramatically in recent years. Potential applications for fiber-reinforced composites (FRC) can be found mainly in prosthodontics, periodontics, and orthodontics.[1-3] Studies have tested polyethylene fibers,[4,5] carbon/graphite fibers,[6-8] Kevlar,[9] and glass fibers[10-14] with varying degrees of success.[15-19] Several in vitro studies have been conducted to determine and understand the factors influencing dental FRC properties.[1,20-31] These factors include the inherent properties of the fibers, matrix, and polymer, fiber surface treatment (sizing), and the impregnation of fibers with resin,[32,33] adhesion of fibers to the matrix,[32] length and form of fibers,[34,35] water sorption of resin matrix,[29] fiber volume fraction,[29,34,36] and the direction, orientation,[28] location, construction, distribution, and position of the fibers.[37-39]

Many methods have been developed to determine optimal fiber orientation.[40,41] Composites with oriented fibers have been previously investigated with a focus on the nature and mechanisms of the alignment and the effects on the mechanical properties.[42] Such studies have often shown anisotropic properties relating to flexural strength (FS),[28] modulus of elasticity,[1] and thermal expansion.[42] Design strategies provide multidirectional reinforcement to minimize the highly anisotropic behavior of unidirectional fiber reinforcement.[43] Short random fibers provide an isotropic reinforcement effect in multidirections instead of only one or two. This is accompanied by a decrease in strength in any one direction when compared with unidirectional fiber, however. Directional orientation of the fiber's long axis perpendicular to an applied force will result in strength reinforcement.[44] Forces parallel to the long axis of the fibers, however, produce matrix-dominated failures and consequently yield little actual reinforcement.[45] While it is known that tension-side fiber reinforcement strengthens a loaded construction, in most instances reported in the dental literature, fiber reinforcement has been positioned in the center of a composite specimen.[45]

It has been emphasized in the literature that increasing fiber volume results in an increase in fracture load in critical areas.[46,47] The peak values of stress, calculated on the outer and inner surfaces of the FRC inlay fixed partial dentures (FPDs) are mostly localized in the connector areas.[48] Kolbeck et al also showed that fractures occurred mainly at the connectors between the pontic and the abutment in combination with a complete fracture of the restoration;[49] however, the connector size limits the main fiber volume in the pontic area, and the primary failure types identified were either bulk fracture at the connector or pontic area, debonding of the veneering composite, or fiber exposure.[50] Therefore, the components of an FRC FPD must be designed to withstand masticatory loading, especially at these critical areas.

Although several studies have evaluated the effect of varying the cross-sectional design in an FRC structure, none has evaluated fibers in a curved position rather than straight, and nearly all studied patterns were in a straight direction. Curved fiber orientation of FRC structures should be investigated and compared with various straight fiber orientations. The aim of this study was to compare the effect of fiber curvature and position on FS, toughness, and elastic modulus in a dental flowable composite test specimen.

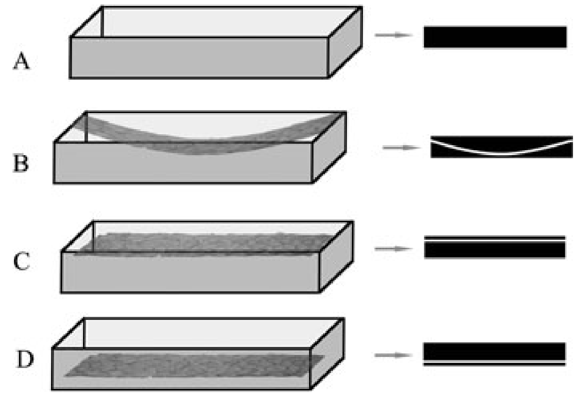

Figure 2 Longitudinal cross-sectional design of the specimens and the resulting pictograms. (A) No fiber reinforcement; (B) fiber reinforcement in curved orientation; (C) in the compression side; (D) in the tension side.

Materials and methods

Four rectangular specimens containing glass fibers embedded within composite in different positions were molded, conditioned, and tested for FS, modulus, and toughness, and the results were used to assess the impact on stress-bearing behaviors. Four groups (n = 10/group) of test specimens (2 mm × 2 mm × 25 mm) were fabricated in a three-piece mold (Fig 1).

Specimens were created with fibers oriented along the long direction of the bars. Positioning of preimpregnated glass fibers (Interlig, Angelus, Brazil) in the test specimens (B–D) is depicted in Figure 2. Unreinforced bars of composite resin (Denfil Flow, Vericom Laboratories Ltd, Anyang, South Korea) were also fabricated in the same way for comparison (group A). The composite and fiber reinforcement (Table 1) were hand-incorporated with special attention to forming the desired design without void inclusions. Care was also taken to maintain alignment of the fibers and to avoid wrinkling or lateral movement, which would affect overall performance characteristics. To orient the fibers in the desired position and curvature, two polyethylene indexes, one for curved fiber position, and the other for straight fiber position, were used (Fig 1). The mold was half-filled incrementally with flowable composite resin. Then the polyethylene index was placed in the correct position and the composite cured for 10 seconds. The index was then removed and the intertwined glass fiber bundle (Fig 3) (2.0 mm × 0.2 mm × 25 mm), preimpregnated (weight accepted = 0.0272 ± 0.0002 g) with light-cured composite resin, and placed in the proper position that had been created with the index. The mold for the test specimens was filled, covered with a transparent Mylar sheet pressed by a glass microscope slide, and polymerized with a hand light-curing unit (Optilux-501, Kerr, CT) for 40 seconds (wavelength: 380 and 520 nm with maximal intensity at 470 nm, light intensity 800 mW/cm^2). Specimens were carefully released from the metal fabrication mold and were post cured in a visible light cure chamber (Targis Power, Ivoclar/Vivadent, Amherst, NY) for 20 minutes. Only specimens with dimensions of 2.0 (±0.1) mm × 2.0 (±0.1) mm × 25 (±1.0) mm were accepted.

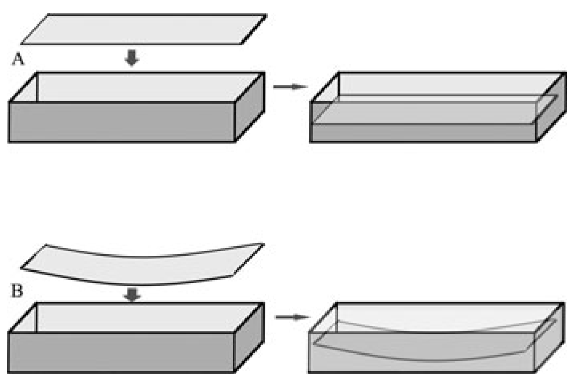

Figure 1 Mold and two indexes used to orient the fibers in the desired position and curvature. (A) Mold, straight polyethylene index, and orientation of index for straight fiber position; (B) mold, curved polyethylene index, and orientation of index for curved fiber position.

All specimens were stored at 37°C in distilled water for 3 days. As it has been reported that polymers show a large variation of physical and mechanical properties with temperature,[40] the specimens were tested immediately after removing from the water. The three-point bending test was conducted according to

Table 1 Materials used

Brand	Manufacturer	Lot no.	Composition
DenFil Flow	Vericom Laboratories Ltd, Anyang, S. Korea	FR8303111	Bis-GMA, TEGDMA, UDMA, Barium glass, Silica
Interlig	Angelus, Londrina, Brazil	10619	Glass fibers (60%), Bis-GMA, diurethane, barium glass, silicon dioxide, catalysts

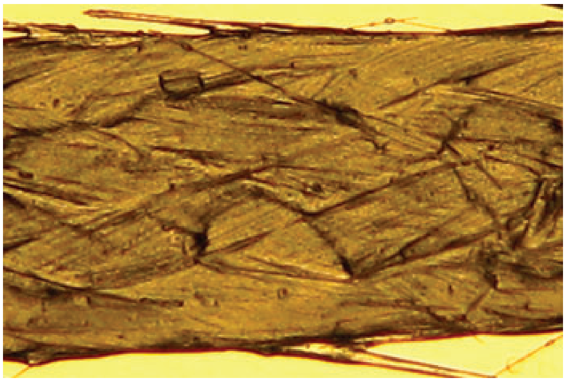

Figure 3 Glass fibers (20× magnification).

ISO 10477 (test span: 20 mm, crosshead speed: 1.0 mm/min, indenter curvature: 2 mm diameter) with the wet specimen directly from the storage container. All specimens were loaded in a universal testing machine (Zwick BZ010/TN 2A, Zwick, Ulm, Germany) and the load-deflection curves were recorded with PC software (TestXpert, Zwick). The setup of the testing machine and recording software were the same as used with the compressive fracture test. The moduli were calculated from the slopes of the linear portions of stress–strain curves. FS was calculated from the following equation:

$$\mathrm{FS} = \frac{3\mathrm{PL}}{2\mathrm{bh}^2}$$

where P is the maximum load exerted on the specimen; L the distance (mm) between the supports; and b the width (mm), and h the height (mm) of the specimen as measured immediately prior to testing.

Flexural modulus (FM) was calculated from the equation:

$$\mathrm{FM} = \frac{\mathrm{FL}^3}{4\mathrm{bh}^3\mathrm{d}}$$

where F is the load (N), at a convenient point in the straight line portion of the trace; d the deflection (mm) at load F; L the distance (mm) between the supports; and b the width (mm), and h the height (mm) of the specimen as measured immediately prior to testing. Loading was continued until either the specimen showed catastrophic rupture or attained a negative slope of load versus displacement with the load drop continuing slowly past peak to below 85% of the peak load.

The toughness (T) of a material can be related both to its ductility and to its ultimate strength. This is an important performance characteristic and is often represented in terms of strain energy, which represents the work required to cause a deformation. This is essentially the area under the load deformation curve and can be calculated as

$$\mathrm{T} = \int_{c}^{x1} \mathrm{Pdx}$$

where P is the applied load and x is the deformation.

Means and standard deviations were calculated and reported. ANOVA and Tukey HSD tests were used to determine the significance of the data within fiber groups for FS (MPa), toughness (MJ), and elastic modulus (GPa). A significance level of $\alpha = 0.05$ was used for all comparisons.

Results

Table 2 shows the mean FS, T, and FM of the specimens. Statistical analysis with ANOVA revealed that fiber reinforcement significantly affected the FS ($p < 0.001$). The data showed that specimens with an FRC substructure provided a higher load-bearing capacity than was obtained with specimens of plain composite. Tukey HSD determined the significance of the data within groups (Table 2). Less difference between materials in terms of FM was found, ranging from 4.7 ± 0.5 to 6.7 ± 0.5 GPa.

Discussion

The results of this study showed that straight fibers positioned in the compression side had the lowest FS among reinforced specimens. These findings are consistent with the results reported by Lassila and Vallittu[45] and Dyer et al[28] as reinforcing fibers at the tensile side improved fracture resistance. This investigation shows that the efficacy of reinforcement depends on both the fiber position and curvature. The straight fibers in the tension side and curved fibers had similar highest strengths, but the curved line fibers had lower stiffness. It could be assumed that specimens with lower stiffness and high strength could distribute forces along the specimens before fracture. Low stiffness and the high FS in this study resulted in the highest toughness in curved orientation of fibers. In planning an inlay FPD, it is often very difficult to design the FRC framework optimally because of the abutment location and occlusal parameters.[45] The proximal boxes usually should be extended to the lowest part of the pontic to place fibers in the tension side. Furthermore, although it has been shown that using a higher volume of fibers causes a higher fracture resistance in FRC FPDs,[2,15–17,43] there are limitations to increasing fiber volume, especially in connectors.

The curved orientation of fibers allows a greater fiber volume fraction and tension side fiber positioning in both pontic and connector area without unnecessary and excessive extension of proximal boxes. Waki et al[3] showed that using curved fibers in the bottom of the pontic provided better reinforcement than reinforcement of the middle of the pontic. Behr et al also reported that anatomically placed fibers in the pontic area that support

Table 2 Mean (SD) of FS, FM, and toughness of different groups

Mean	Pictogram	Flexural strength (MPa)	Flexural modulus (GPa)	Toughness (MJ)
A		117(5)	4.7(0.5)	26(8)[c]
B		174(8)[a]	5.7(0.3)	83(28)
C		132(12)	6.4(0.3)[b]	21(4)[c]
D		173(11)[a]	6.7(0.5)[b]	36(3)[c]

Ten specimens were involved in each test group.
Statistical comparisons are within the columns, and similar superscript letters denote groups not statistically different ($p > 0.05$) for each test.

all parts of the pontic improve the fracture resistance of FRC FPD.[20] Direct comparison with previous studies is not always possible, however, because factors such as the fiber volume fraction, location of the fiber-rich phase in the test specimen, bending test span-length-height ratio of the specimen, and the nature of composite resin may have an effect on the resultant FS values.

Magne et al[21] carried out a finite element analysis to simulate stresses to the surface and interface of a 3-unit adhesive inlay FPD. They showed that FRC and all of the materials used in the study had similar stress patterns with a definite tensile zone at the gingival portion of the pontic. This tensile zone was a curved shape, which was parallel to the gingival surface of the pontic.[21] They also showed that stiff materials resulted in higher stresses in the adhesive surface of FPDs, which may cause retention loss and subsequent failure.[21]

The nature of the overlying veneering composite plays a critical role in relation to the physical properties of the FRC.[51] In this study, flowable composite was used for better comparison of different patterns of fiber reinforcement. The FS of fiber-reinforced restorations may be improved with the use of new polymer formulations with high filler particle distribution. [37]

The results of this study are somewhat in agreement with those of Lassila and Vallittu.[45] They showed that the position of the FRC layer did not have a significant effect on the FM, probably because the stiffness of the fibers was considerably higher than that of the polymer matrix. Thus, the stiffness of the test specimen was mainly influenced by the modulus of the fiber layer.

Although polyethylene indexes were used to fabricate specimens, the overall fabrication technique is classified as a hand lay-up process. The hand lay-up process is typically subject to more errors in FRC fabrication than other techniques, and this may justify relatively large standard deviation values. Because the modulus values were recorded directly from crosshead movement rather than from strain gauges, there would be some errors based on the compliance and stiffness of the test apparatus, and this could be potential problem with the data.

Clinical conditions may be more critical than those simulated in vitro and potentially may result in lower forces creating failure. Water exposure could cause a variety of weakening effects on the resin matrix, which accelerates crack growth. Cyclic loading is also able to promote crack growth.[52,53] As water absorption, aging, thermocycling, and cyclic loading could affect the mechanical properties of FRC materials, fatigue loading complex specimen designs in dry and wet environments could better address questions related to masticatory loading in the oral environment. Another limitation of this study was that specimen dimensions followed standard specimen design rather than a three-unit fixed prosthesis, and there may not be enough length clinically to get the same effect observed in this examination. Despite these potential limitations, however, the results of this study support further clinical investigation in this area.

Conclusion

Within the limitations of the present experiment, it could be concluded that FRC substructure provided a higher load-bearing capacity than was obtained with specimens of plain composite ($p < 0.001$). Also by positioning fibers in a curved position, toughness of FRC materials was increased (toughness = 83 MJ).

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