

ORIGINAL ARTICLE

Effect of continuous longitudinal glass fiber reinforcement on the cantilever beam strength of particulate filler composites

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Abstract

Objective. The objective of this *in vitro* study was to investigate the effect of continuous longitudinal glass fibers on the bending properties of particulate filler composite resins. **Material and methods.** Four particulate filler composite resins (Tetric Ceram, Point 4, Z250, P60) and one continuous longitudinal glass fiber material (everStick) as reinforcement were selected. Three groups of beam specimens (5 × 5 × 25 mm) for each material were fabricated. For group I, specimens were not reinforced with fibers and were tested as the control group. For group II, specimens were reinforced with 2 layers of the fiber (6.5 vol%), and for group III with 3 layers (9.8 vol%). The specimens were stored at 37°C for 30 days. One end of the beam specimen (14 mm) was fixed in a device, while the other (11 mm) was left free. Cantilever beam strength was measured using a universal testing machine, loading at a distance of 10 mm from the upright support through a steel ball of 2 mm diameter. The loads and deflection at initial failure and at final failure for each specimen were recorded. The data were statistically analyzed using one-way ANOVA and the multiple comparison Scheffé test ($\alpha=0.05$). **Results.** The bending moments of particulate filler composite at final failure, when reinforced with 3 layers of the glass fibers (272.4–325.2 Ncm), were significantly higher than for the composites without fibers. However, the materials reinforced with 3 layers of fibers were not significantly different from the materials reinforced with 2 layers of fibers (234.1–282.6 Ncm). The materials reinforced with 3 layers of fibers exhibited severe deflection at final failure, ranging from 2.8 mm to 3.4 mm. The bending moments of the particulate composites increased linearly with the weight fraction of the fillers, but there was no linear correlation between them when reinforced with fibers. **Conclusions.** The cantilever beam strength of the particulate filler composites increased significantly when layers of fibers were added and as the weight fraction of filler increased, but a higher fiber volume fraction did not lead to a significantly higher cantilever beam strength.

Key Words: Bending moment, fiber-reinforced composite

Introduction

Among the various treatments for replacing missing teeth are conventional fixed partial dentures (FPDs), removable partial dentures, and implant prostheses. Cantilever FPDs may be an alternative treatment choice. The cantilever FPDs, which are usually used when replacing a natural tooth, do not improve masticatory efficiency, but they do prevent the physiologic movement of opposing teeth or encourage stability of an opposing removable prosthesis [1]. Extensive cantilever FPDs can be used in the rehabilitation of patients with very reduced dentition and a history of difficulty in adapting to removable dentures [2]. The need for cantilever FPDs persists [3,4].

Metal-ceramic restorations have been widely used in the past several decades owing to their high mechanical strength, good clinical longevity, and acceptable esthetics [5]. They can be used for cantilever FPDs, but the porcelain can fracture as a result of increased bending movement at the junction between the pontic and retainer. Although all ceramic restorations show excellent esthetics, they are brittle. High costs and time-consuming luting techniques are additional main limiting factors [5]. They fail more frequently than metal-ceramic restorations [6]. Fiber-reinforced composite (FRC) restorations used for fixed prostheses consist of a particulate filler composite and a fiber framework. Indirect composite resin systems have been developed to offer higher fracture toughness and a higher degree of conversion

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than conventional composite material, but they cannot be used alone for fixed prostheses because of their low strength. However, this can be overcome by using a fiber framework that gives the prostheses strength and rigidity [7]. In the case of a glass-fiber framework, the fibers bond with an overriding particulate composite resin chemically via silane coupling agents [8,9]. The combination between the fiber framework and the particulate filler composite resin gives a metal-free restoration with advantages [10,11] such as high translucency, excellent esthetics, no corrosion from galvanism [12], no potential hazards of working with base metal alloys [13], use of adhesive luting technique [14], and no distortion of magnetic resonance imaging [15].

Among several criteria for the success of cantilever FPDs – such as adequate periodontal support, favorable root length, sufficient crown length, parallel-sided walls, vital abutment teeth, harmonious occlusal relationship, adequate oral hygiene, sufficient connector, rigid restorative material and a favorable stress distribution [4,16] – a critical factor related to materials for the cantilever FPD is high mechanical strength. When occlusal force is applied to the pontic of the cantilever FPD, a class I lever system is created [17,18]. The system can induce vertical bending moments and vertical bending stresses in the connector mesial to the distal cantilevered pontic [19,20]. The connector is thus the weakest part. Eighty-three per cent of fractures occur on the distal part of the most distal abutment tooth [21]. If its modulus of elasticity and strength are low, excessive bending of the cantilever FPD occurs, resulting in incomplete function as a prosthesis. Therefore, materials for the cantilever FPD should have high mechanical strength and the connector should have sufficient thickness to prevent deformation or fracture of the prosthesis. FRC materials have been widely investigated, but there is a lack of information about their cantilever beam strength. The objectives of this study were: (i) to measure maximum bending moment and maximum deflection of the particulate filler composite materials at failure, (ii) to evaluate the magnitude of the bending properties of specimens incorporating different amounts of continuous longitudinal glass fibers, and (iii) to evaluate the correlation between the filler content of the composites and the bending moment. The null hypothesis to be tested was that there was no difference in the cantilever beam strength between composite material without fiber and fiber-reinforced composite material.

Material and methods

Materials

The materials under investigation were four commercially available visible-light activated composite resins and one fiber material as reinforcement (Table I).

Table I. The materials investigated in this study

Material	Code	Lot no.	Shade	Manufacturer
Tetric Ceram	TRC	BO8986	A1	Ivoclar Vivadent, Schaan, Liechtenstein
Point 4	PT4	911273	A3	Kerr, Orange, California, USA
Z 250	Z250	6020A1	A1	3M-ESPE, St. Paul, Minn., USA
P 60	P60	2e+07	A3	3M-ESPE, St. Paul, Minn., USA
everStick	–	Not available	–	StickTech Ltd., Turku, Finland

This fiber is a semi-manufactured product made of unidirectional glass fibers, thermoplastic polymer, and light-curing resin matrix.

Preparation of specimens

Beam specimens were prepared in a silicone mold made of Flexistone Plus (lot no. 000803, Detax, GmbH & Co. KG, Ettlingen, Germany). The overall external dimensions were $5 \times 5 \times 25$ mm. Each specimen had the same cross-sectional geometry. Specimen geometry and the position of the fibers in the specimens are shown schematically in Figure 1. Three groups of each material were prepared for this experiment. For group I, specimens were not re-

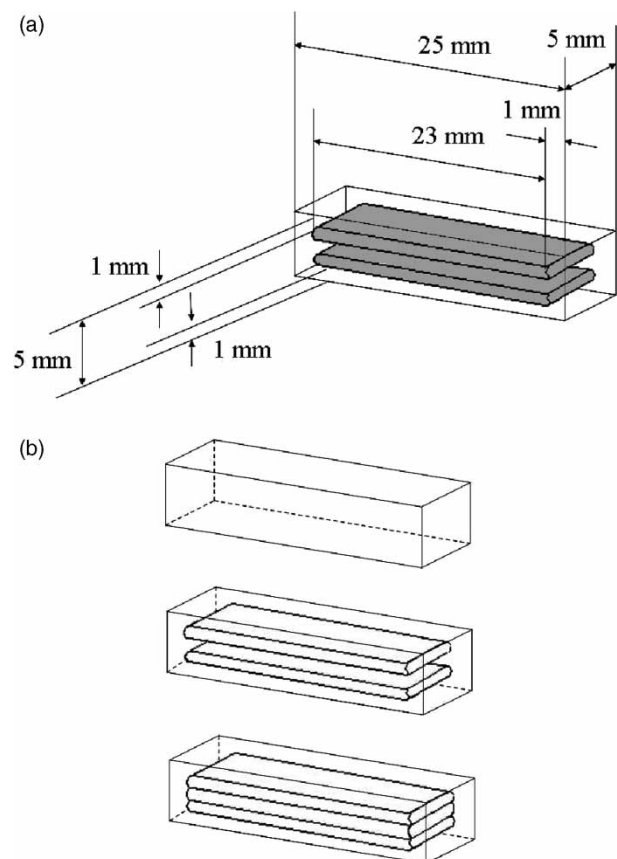


Figure 1. (a) Specimen geometry. (b) Position of the fibers in specimen. Top: Group I. Middle: Group II. Bottom: Group III.

inforced with the fibers, and were tested as the control group. For group II, specimens were reinforced with 2 layers of the fiber, and for group III with 3 layers.

For group I, composites were placed in the mold using a layer technique. The mold was half-filled with the material and packed using a plastic hand instrument. Visible light was irradiated to right, center, and left areas of the material in the mold for 3×40 s using a curing unit (Curing Light XL 3000; 3M-ESPE, St. Paul, Minn., USA). The mold was then filled with the material using the same technique. When the mold was filled to the top with the material, it was covered with a cellulose acetate matrix supported by a glass plate. High pressure was then applied vertically by hand and further visible light was irradiated onto the surface of the specimen. After the specimen was removed from the mold, more visible light was directed for 3×40 s to the other longitudinal surfaces of the specimen to ensure complete polymerization. The thin flash of excess material was removed by lightly rubbing on 800 grit sandpaper under wet conditions, thus further ensuring that both surfaces were parallel.

For groups II and III, the specimens were reinforced with fibers. A layer of composite resin of approximately 1 mm thickness was first placed in the mold; the fiber was cut with sharp-edged scissors to a length of 23 mm and then placed on top of the composite layer in the center of the mold. For group II, a thin layer of composite resin of approximately 1 mm thickness was also placed in the mold. Another fiber of the same length was placed on the composite and then covered with the composite. For group III, two more fiber layers of the same length were placed on the first fiber layer. The remainder of the mold was filled with the composite resin. The remaining procedures were the same as for group I. Five specimens ($n=5$) for each group were prepared. After completion of finishing and polishing, all specimens were placed in a labeled bottle containing distilled water and the bottles were stored in an oven at 37°C for 30 days before mechanical testing.

Mounting of the specimens

Beam specimens were fixed in a specially designed device (Figure 2) consisting of two horizontal rectangular plates connected by four vertical bars. One end of the beam specimen, 14 mm from the edge, was inserted between the two plates. The upper plate was placed in contact with the specimen and screws were tightened against the vertical bars to compress the upper horizontal plate against the top surface of the beam specimen. One end of the beam specimen (14 mm) was fixed and the opposite end (11 mm) was free.

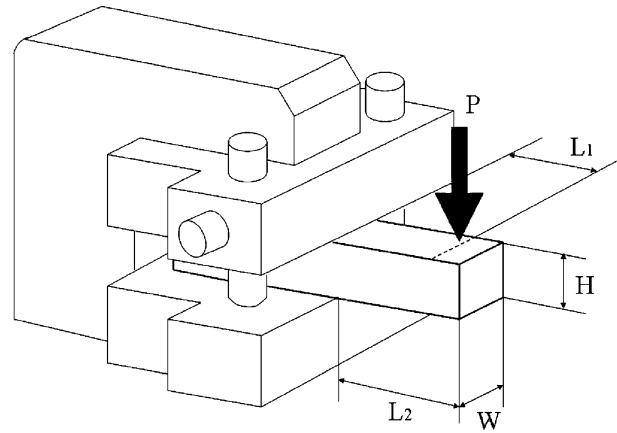


Figure 2. Beam specimen and the device for cantilever beam strength test. $L_1 = 10$ mm, $L_2 = 11$ mm, $H = 5$ mm, $W = 5$ mm.

Mechanical loading

All beam specimens were loaded using the Howden Universal Testing Machine (RDP; Howden Ltd., Southam, Warks, UK) operated at a cross-head speed of 0.5 mm/min. A load was applied to the free end of the specimen, 10 mm from the upright support, through a steel ball of 2 mm in diameter (Figure 2). The load was applied until failure of the specimen occurred. For fiber-containing specimens, two loads at initial and final failure were recorded. In this study, the initial failure was defined when the upper part of the specimen fractured with a sudden sharp sound (the crack propagation was inhibited by the presence of fibers), and the final failure when maximum load during failure was seen. Analog load/deflection curves were also recorded. Bending moment (Ncm) at the support and the deflection (mm) of each beam specimen were calculated.

Particulate filler and fiber content

The particulate filler and fiber content of each specimen tested as a percentage by weight were measured by combustion analysis. Conversion into the fiber content as a percentage by volume was carried out using the following equation:

$$V_f = \frac{W_f/D_f}{V_s} \times 100$$

where W_f is the weight of the fiber, D_f is the density of the fiber (2.54 g/cm^3), and V_s is the size of the test specimen ($5 \times 5 \times 25 = 0.625 \text{ cm}^3$).

Statistical analyses

The mean values and standard deviations of the results were computed. The effect of continuous longitudinal glass-fiber reinforcement on bending moment and deflection between groups was statistically evaluated using one-way ANOVA and the multiple comparison Scheffé test at the significance level of 0.05. Linear regression analysis was also

applied. SPSS (version 12.0, SPSS Inc., Chicago, Ill., USA) was used for the statistical analyses.

Results

The mean values and standard deviations of bending moment and deflection of each material are given in Table II.

In the specimens without fibers, Z250 showed the highest mean bending moment, followed by P60, PT4, and TRC, but there were no significant differences between materials. TRC showed the highest deflection followed by Z250, P60, and PT4. Significant differences were found between TRC and PT4 or P60.

In the specimens reinforced with 2 layers of the fiber, both at initial failure and at final failure there were no significant differences between materials in either bending moment or deflection.

In the specimens reinforced with 3 layers of the fiber, both at initial failure and at final failure there were no significant differences in bending moment between materials. At initial failure, Z250 showed the highest deflection, and there were no significant differences between materials except between TRC and Z250, but at final failure no significant differences were found between materials.

When the control group and the 2-layer fiber group were compared, at initial failure, bending moments did not increase significantly when reinforced with 2 layers of the fiber except with TRC. At final failure, the maximum bending moment of all materials increased significantly. The bending moments of TRC, PT4, Z250 and P60 increased by 43.2%, 53.8%, 37.1%, and 36.9%, respectively.

When the 2-layer and 3-layer fiber groups were compared, the bending moment of the specimen reinforced with 3 layers of the fiber did not increase significantly, either at final failure or at initial failure. However, in PT4 and Z250, significant differences were found between the 2-layer fiber group at initial

failure and the 3-layer fiber group at final failure. Significant differences in the deflection were not found between the 2-layer fiber groups at final failure and the 3-layer fiber groups at initial failure.

When the control group and the 3-layer fiber groups were compared, at initial failure the bending moment of TRC and PT4 was significantly increased. At final failure, when the specimen was reinforced with 3 layers of the fiber, the bending moment of all specimens was significantly increased. The bending moments of TRC, PT4, Z250, and P60 increased by 66.7%, 91.1%, 50.0%, and 57.1%, respectively.

Fiber volume fractions of the specimens reinforced with 2 layers and 3 layers of the fiber were 6.5 vol% and 9.8 vol%, respectively. The mean particulate filler weight fractions of TRC, PT4, P60, and Z250 were 72.2 wt%, 73.8 wt%, 79.0 wt%, and 79.9 wt%, respectively, by combustion analysis. The regression analysis in Table III indicates that the bending moment of the particulate filler composites increased as the weight fraction of filler increased ($R=0.995$, $p=0.005$). However, there was no linear correlation between them when it was reinforced with fibers except at initial fracture of 3 layers of fiber.

Discussion

The cantilever beam strength test, which is common in engineering for the study of materials, is one of the methods used to measure the flexural strength of a beam. The cantilever beam has rigidity from the bonding forces between the neighboring atoms that affords resistance to deformations. When a load is applied at the free end of a cantilever beam, the beam is subjected to combined bending and axial compressive stresses, but the bending stress is the dominant component, being greater than the axial compressive stress. The upper half of the beam stretches in tension, while the lower half compresses

Table II. Mean and standard deviation in parentheses of Moment (Ncm) and Deflection (mm) at the maximum moment

Mat.	Group I		Group II				Group III			
	Final failure		Initial failure		Final failure		Initial failure		Final failure	
	Moment	Deflection	Moment	Deflection	Moment	Deflection	Moment	Deflection	Moment	Deflection
TRC	163.4 ^{A,B,C,D} (30.6)	0.61 ^{a,b,c,d} (0.06)	223.2 ^A (16.3)	1.91 ^{a,c} (0.35)	234.0 ^B (30.8)	2.20 ^{b,f} (0.39)	229.4 ^C (18.3)	1.72 ^{c,g} (0.14)	272.4 ^D (28.1)	3.29 ^{d,e,f,g} (0.30)
PT4	170.2 ^{E,F,G} (30.6)	0.47 ^{h,i,j,k} (0.04)	226.0 ^H (37.3)	1.94 ^{h,l} (0.29)	261.8 ^E (25.4)	2.69 ⁱ (0.53)	244.0 ^{F,I} (34.8)	1.98 ^{j,m} (0.27)	325.2 ^{H,G,I} (24.2)	3.40 ^{k,l,m} (0.66)
Z250	206.2 ^{J,K} (8.0)	0.52 ^{n,o,p,q} (0.06)	240.4 ^L (28.4)	1.88 ^{n,r} (0.15)	282.6 ^J (34.9)	2.68 ^o (0.51)	275.2 (25.0)	2.18 ^{p,s} (0.15)	309.2 ^{K,L} (25.7)	3.41 ^{q,r,s} (1.02)
P60	197.2 ^{M,N} (29.3)	0.49 ^{t,u,v,w} (0.05)	249.2 (38.4)	1.82 ^{t,x,y} (0.11)	270.0 ^M (24.0)	2.26 ^{u,x,z,2} (0.19)	262.0 (26.9)	1.77 ^{v,z,3} (0.21)	309.8 ^N (44.9)	2.82 ^{w,y,2,3} (0.25)

Mat = Material, M = Moment, D = Deflection.

The same superscript letters denote significant differences between two groups at the significant level of 0.05.

Table III. Correlation coefficient between filler weight fraction and bending moment

	Bending moment	R	R ²	Significance
Control group	At fracture	0.995	0.990	0.005
2-layer fiber group	At initial fracture	0.920	0.846	0.080
	At final fracture	0.906	0.822	0.094
3-layer fiber group	At initial fracture	0.977	0.955	0.023
	At final fracture	0.451	0.203	0.549

in compression. It follows that there is a region of zero stress between the two surfaces. The region is called the neutral axis [22]. Stress distribution and strain varies linearly throughout the depth of the beam, from zero at the neutral axis to a maximum at the surface under compression or tension. The bending moment varies from zero at the point of load application to a maximum at the built-in end [22]. When the load is within the elastic deformation range, the inter-atomic forces allow for some deformation. When the applied load is removed, the beam recovers its original shape as the inter-atomic distances return to equilibrium. However, when the load exceeds the elastic deformation limit, plastic deformation and/or microcracks develop first in the cantilever beam. These cracks extend through the matrix in the direction of the fiber. When resin matrix and fibers are poorly bonded together, delamination occurs, resulting in release of stored energy, which drives the separation process. Finally, fiber fracture occurs [23], the characteristics of which determine the stiffness and strength of the beam [23,24]. With increasing stress, fibers continue to break randomly throughout the material, and when a fiber breaks there is a redistribution of stress near the fracture site. In this test, most specimens reinforced with fibers did not fail catastrophically, because the specimen had a large number of load-carrying fibers, but delamination occurred and the material bent severely without showing total fracture of the fibers.

Height and width of the specimens used in this study were both 5 mm, simulating the recommended height and width of the connector of a FPD, which have to be above 4 mm [25,26]. However, the properties of fiber-reinforced composite materials are determined by the fiber volume fraction and the manner in which the fiber and resin matrix interact with each other. This critical interaction is controlled by the bonding between the constituents. Voids between the matrix and the fiber caused by incomplete impregnation reduce the load-bearing capacity, as a stress concentration usually develops in a localized region of voids. The mechanical properties of composites are greatly reduced when the void concentration exceeds 5% by volume [13]. In addition, voids increase water sorption of the material, resulting in hydrolytic degradation, inhibition of the radical polymerization, and discoloration of the

material [27–29]. It is therefore important to achieve a good bond between the fibers and the high viscosity resin matrix. The fiber used for reinforcement in this study was a light-polymerizable resin preimpregnated material devised to increase the degree of impregnation and to reduce the possibility of poor bonding to the resin matrix [8,29].

This *in vitro* test indicated that the bending characteristics were related to the presence of fiber in the composite. All materials tested showed a significant increase in the bending moment when reinforced with 2 or 3 fiber layers. Therefore, the null hypothesis that there was no difference in the cantilever beam strength between composite materials without fiber and fiber-reinforced composite materials could be rejected. The increase in the cantilever beam strength was caused by the reinforcement of the fibers. Half of the fibers were placed above the neutral axis, namely, on the tension side of the specimen. The fiber reinforcements increased the elastic modulus of the specimen, but no significant differences in cantilever beam strength were found between the 2-layer and 3-layer fiber groups. This could be explained by the fiber content above the neutral axis. In this test, when 3 layers of the fiber were placed in the specimen, half of them were positioned on the compression side of the specimen and half on its tension side. As a result, the quantity of fiber above the neutral axis was not enough to increase the cantilever beam strength significantly. It thus seems that the position of the fiber in the structure was a more important factor for flexural beam strength than the fiber fraction, but more research is needed to evaluate the effect of fiber reinforcement depending on the position in the structure and the fiber content.

The maximum bending moments of the specimens reinforced with 3 layers of the fiber ranged from 272.4 to 325.2 Ncm. The specimens, however, exhibited severe deflection caused by the deformation of fibers at the applied loads, ranging from 2.8 to 3.4 mm. The fibers in the specimen held the fractured pieces together although fracture occurred. If a similar amount of deflection were to occur when occlusal force is applied, the prostheses would not continue to function in the mouth. Thus, when the cantilever FRC restoration is fabricated with the same materials and the same geometry tested in this

study, there should be more than 3 layers of fibers to prevent abrupt catastrophic failure and severe deflection of the restoration, and all fibers should be positioned on the tension side of the restoration to maximize the reinforcement effect. In addition, the length of pontic extension should be short, because an increased risk of failure with increasing number of cantilever units has been reported [21,30,31]. Randow et al. [21] found that the frequency of technical failures of cantilever FPDs was directly related to the degree of cantilever extension. The rate of failure increased with time, and this tendency was much more severe with multiple cantilever pontics. Karlsson [31] found a failure rate of cantilever FPDs of 33%, which was higher than that of conventional FPDs (12%). Thus, strict adherence to principles such as optimal retention, adequate framework design, thick framework dimensions for rigidity, short extension length of cantilever pontics, and specific occlusal design criteria, is critical.

Matrix toughness, which is related to the filler loading, is also a critical factor in the development of microcracks in the matrix. This study showed that the bending moments of cantilever beam specimens increased with the filler loading of the particulate composites. This increase was in accordance with the study by St. Germain et al. [32]. Higher filler content increases the energy required to develop and to extend a crack. However, the resulting values of FRC strengths and deflection of the cantilever beam are dependent upon on a variety of factors, including the beam configuration, the properties, geometry, arrangement and bonding of the constituents, the amount of load, the direction of load, the type of load, material stiffness and the geometry of the cross section. Thus, other factors should be addressed in future studies.

Within the limitations of this study, the following conclusions can be drawn:

1. The maximum bending moment of composite resins reinforced with 3 layers of continuous longitudinal glass fibers (272.4–325.2 Ncm) is significantly higher than that of composite resins without fibers, but this is not significantly different from that of composites reinforced with 2 layers of fibers (234.0–282.6 Ncm).
2. Deflection of the specimens with 3 layers of fibers at final failure ranges from 2.8 to 3.4 mm.
3. The bending moment of the particulate filler composites increases as the weight fraction of filler increases, but there is no linear correlation between them when reinforced with fibers.
4. It is recommended that the cantilever length of composite resin reinforced with 3 layers of fibers is kept short to prevent excessive bending.

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