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Short fiber reinforced composite in restoring severely damaged incisors

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Abstract

Objective. To evaluate the static-load-bearing capacity of severely damaged endodontically-treated incisors restored with short fiber composite (SFC) as a direct post-core-crown complex and to investigate the effect of SFC on the failure mode of the restorations. ***Materials and methods.*** The clinical crowns of 40 maxillary incisors were prepared by cutting 2/3 parts of the crown horizontally. Five groups were fabricated ($n = 8$) using the direct technique; Group A: Crown restorations from conventional composite (CC); Group B: FRC-posts with core-crown restorations from CC; Group C: Crown restorations from SFC; Group D: FRC-posts and core-crown restorations from SFC; Group E: Post–core-crown restorations from SFC. The posts were cemented with dual-cure resin cement. The restorations were polymerized with a hand-light curing unit. All restored teeth were stored in distilled water at 37°C for 5 days before they were statically loaded. Initial fracture (IF) and final fracture (FF) were recorded. Failure modes were visually examined. ***Results.*** ANOVA revealed that SFC restorations had greater IF (469.8 N) and FF load values (515.8 N) ($p < 0.05$) than the CC restorations (164.8 N). No significant difference for both IF and FF was observed among groups C, D and E. Group E revealed a more favorable fracture mode than any other material combination used. ***Conclusion.*** The use of SFC as a restorative material for fabricating the direct composite post-core-crown restorations of severely damaged incisors provided improved load-bearing capacity than CC used alone or with FRC post reinforcement.

Key Words: *direct composite post-core-crown restoration, FRC post, load-bearing capacity*

Introduction

Severely damaged anterior teeth with fractured crowns or endodontically-treated weakened and discolored anterior teeth are often restored with complete crowns as definitive restorations. When anterior teeth possess insufficient tooth structure to retain the coronal restoration, treatment involves endodontic therapy followed by a post placement. Insertion of a post and core as a foundation restoration is required when more than half of the coronal tooth structure has been removed from an endodontically-treated tooth (ETT) [1]. The role of the post is to improve the retention of the core to the remaining tooth structure rather than to reinforce endodontically-treated teeth. The amount of residual dentin influences the strength of ETT and is important because the dentin is removed while preparing the post space. The conservation of inner dentin is crucial because it gives toughness or fracture resistance to the tooth structure [2]. In turn, removal of inner dentin during post-endodontic restoration pre-disposes the tooth to catastrophic fracture [2]. In the study of Ferrari et al. [3], residual coronal dentin appeared to influence tooth survival significantly and failure risk was significantly higher for teeth that had lost all coronal walls. In other words, when minimal dentin remained, teeth treated with a post performed better than those treated without a post. Hence, the longevity of post-restored teeth is not attributed to the characteristics of the post alone. Other factors that should be additionally considered are the luting medium, core and composite crown restorative material, crown design, position of the tooth in the arch, the load experienced by the tooth and the amount as well as the quality of the remaining tooth structure.

If more than 50% of the coronal portion of the clinical crowns are lost, direct core restorations using either titanium or zirconia posts are suitable restorations [4]. However, the titanium posts used in the study of Heydecke et al. [4] were either bent or dislodged from the root canal, while all the zirconia posts fractured. Unrestorable fractures for zirconia

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post are also reported by other authors [5,6]. Due to lower survival rates, the combination of zirconia post with composite core is not recommended for clinical use [7]. Furthermore, cast posts [6,8–10] and pre-fabricated metal posts [5,6,8,9] contribute to the fracture of the root, carbon-FRC posts with composite cores are associated with failure of the post/core interface [10] and the fracture of the core and/or portion of the core–tooth interface is also observed with pre-fabricated posts modified with polyethylene woven fiber ribbon [9]. Based upon this, one may conclude that FRC posts protect the tooth from root fracture and tooth loss which gives a better tooth prognosis. Among pre-fabricated non-metal posts, glass fiber-reinforced posts possess many advantages as fundamental differences exist in the fracture strength and failure rates when compared to metallic posts used with a resin composite core [11]. A stronger union between crowns and endodontically compromised teeth can be achieved by using resin-bonded-fiber-reinforced posts and composite cores, rather than conventional cast dowels and cores [12].

Recently, FRC posts made of a material having silanated glass fibers impregnated with an interpenetrating polymer network (IPN) resin matrix have been introduced to the market [13–17]. While a pre-fabricated FRC root canal post consists of reinforcing fibers (carbon, glass, quartz) and a fully polymerized resin matrix among the fibers forming a solid post with a predetermined diameter, the individually formed FRC posts are made of non-polymerized fiber-resin-pre-impregnated posts, consisting typically of glass fibers and a light-curing resin matrix [14]. Pre-fabricated FRC posts have a cross-linked nature, while individually formed FRC posts are formed with a semi-IPN- polymer matrix, comprised of both linear and cross-linked polymer phases. Monomers that have solubility parameters resembling PMMA as bis-GMA, TEGDMA and HEMA are able to penetrate into the IPN polymer matrix [15]. These monomers are used as a main ingredient in the bonding resin systems currently employed, as adhesive resins and composite resin luting cements. By penetrating into the IPN polymer structure and dissolving the linear polymer phase, the inter-diffusion bonding occurs, therefore enhancing the adhesion between the post and both the luting cement and the tooth structure.

On the other hand, the composite resins used to fabricate the direct core and/or the direct composite crown restorations must have appropriate physical and mechanical properties as well as an adequate esthetic appeal. However, present resin composites still have shortcomings limiting their application. Attempts were made in terms of improving the properties of conventional composites (CC), for example by adding reinforcing fibers [18].

Recently, a short fiber composite (SFC) was introduced as a dental restorative composite resin of the semi-IPN-polymer matrix in combination with short glass fibers [19–23]. This composite is intended to be used in high stress bearing areas. The results of the mechanical tests revealed substantial improvements in the load-bearing capacity and the flexural strength of the composite resin reinforced with short E-glass fiber fillers in comparison with a CC [19]. The short fiber composite resin has also revealed improvements in polymerization shrinkage stress and marginal microleakage compared with a CC [20]. It is used to mend severely damaged incisors with direct composite crowns made from SFC with and without a FRC sub-structure [21], as a post-core restorative material showing improved load-bearing capacity compared with a CC [22], as well as a direct restorative material used plain or with a FRC post in repairing severely damaged canines [23].

The development of alternative treatment methods which use an adhesive bonding technique and a minimal post placement that restores ETT, accompanied by a directly made composite core covered with a composite crown restoration, continues to occur. The authors of this study hypothesized that restorations made from a composite resin reinforced with a short E-glass fiber filler with a semi-IPN-polymer matrix (SFC) as a dental material of choice for both the post-core foundations and the direct composite crown restorations can sustain the load required for a direct post-core-crown complex and may count as an alternative method for restoring a severely damaged incisor.

The aim of this study was to evaluate the static-load bearing capacity of severely damaged endodontically treated maxillary central incisors restored with SFC with a semi-IPN-matrix as a direct post-core and crown restorative material and to investigate the effect of SFC on the failure mode of the restorations.

Materials and methods

The materials used in the study are listed in Table I. Short fiber composite resin (SFC) was prepared by mixing 22.5 wt% of short E-glass fibers (3 mm in length, 15 μm in diameter, coated with PMMA and BisGMA matrix) to 22.5 wt% of photopolymerizable dimethacrylate resin matrix and then 55 wt% of silane-treated silica fillers (3 ± 2 μm in size) (Aldrich, Steinhein, Germany) were added gradually to the mixture. The mixing was carried out by using a high speed mixing machine for 5 min (SpeedMixer, DAC, Germany, 3500 rpm). The dimethacrylate-based resin matrix containing PMMA was supposed to form a semi-IPN polymer matrix for the short fiber composite resin.

Table I. Materials used in the study.

Brand	Manufacturer	Lot No.	Monomer & fiber content	Type of material
Short fiber composite (SFC)		2100524-D7-022	22.5wt% short E-glass, PMMA, bis-GMA, 55wt% silane treated silica filler	Visible-light activated short fiber composite.
Stick Resin	Stick Tech Ltd., Turku, Finland	5709295	bis-GMA, TEGDMA	Unfilled light-curing resin.
everStick	Stick Tech Ltd., Turku, Finland	2060727-ES-158	E-glass, PMMA, bis-GMA	Resin-pre-impregnated continuous unidirectional FRC.
Supreme (CC)	3M, St Paul, MN	20090707	bis-GMA, UDMA, TEGDMA, bis-EMA, 78.5 w% zirconia/silica cluster filler and a non-agglomerated-aggregated silica filler	Visible-light activated, restorative nanocomposite.
ScotchBond multi-purpose etchant, primer and adhesive	3M, St Paul, MN	20090516 Etchant: 9NR Primer: 9CE Adhesive: 9RM	Etchant: 35% phosphoric acid; Primer: HEMA, water, vitrebond copolymer; Adhesive: HEMA, bisGMA	Etchant: Phosphoric acid based etchant material; Primer: Water based primer material; Adhesive: Unfilled light-polymerizible bonding resin.
ParaCem® Catalyst	Coltène/Whaledent AG, Altstätten, Switzerland	0144828	bis-GMA, bis-EMA, TEGDMA, Barium glass silanized, Amorphous silica, Benzoyl peroxide	Dual-curing cement.
ParaCem® Base	Coltène/Whaledent AG, Altstätten, Switzerland	0148324 (A3)	bis-GMA, bis-EMA, TEGDMA, Barium glass silanized, Amorphous silica, Initiators	Dual-curing cement.

PMMA, polymethylmethacrylate; bis-GMA, bisphenol-A-glycidyl dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate; HEMA, hydroxyethylmethacrylate; bis-EMA, bisphenol-A-dyethoxy dimethacrylate.

Specimen preparation

Forty extracted endodontically-treated human maxillary central incisors with straight roots and fully developed apices were selected on the basis of similar root dimensions, absence of caries and fillings in the cervical and root areas, absence of visible fracture lines or cracks in the root that might affect the fracture resistance to the static-load and a clinical crown up to 2 mm above the cemento-enamel junction (CEJ). The teeth were cleaned of soft tissue and calculus and were stored in water in order to prevent desiccation until further processing. Root lengths were measured with a digital calliper (Tamoline, Helsinki, Finland) with an accuracy of 0.01 mm from CEJ on the labial surface and mesiodistal widths were measured between the proximal surfaces at the CEJ. The teeth selected for this study had a mean length value of 22.0 ± 0.5 mm and a mesiodistal mean dimension of 6.3 ± 0.1.

The clinical crowns of all teeth were prepared by cutting the incisal and the middle (two-third; 2/3) part of the crown perpendicularly to the long axis of the tooth, using a 1000-grit silicon carbide abrasive paper (Struers, Copenhagen, Denmark) at 300 rpm under water cooling with a grinding machine (Struers, Labo-Pol-21, Struers, Copenhagen, Denmark).

Bonding procedure, post fabrication and cementation

The teeth with one-third (1/3) of the coronal structure remaining were restored with direct composite post-cores and direct composite crowns according to the groups they belonged (Figure 1). Five groups were fabricated ($n = 8$) using the direct technique of incrementally building-up the composite core and crown restorations. The first (control) group and the third group were composed of teeth restored with resin composite, either with plain CC (Group A) or with plain SFC (Group C) as restorative materials for fabricating the direct composite crowns without post. The second group (Group B) was composed of teeth restored with CC and the fourth group (Group D) with SFC as a direct composite core and crown restorative material, reinforced in both groups with individually-formed FRC posts. The fifth group (Group E) was composed of teeth restored with SFC as a direct composite post-core foundation and crown restorative material.

The removal of the root filling material and root canal, i.e. post space preparation, were not performed in Groups A and C. The direct composite crown restorations were directly fabricated over the flattened coronal surface. The remaining coronal structure was firstly etched for 15 s using a 35% phosphoric acid (Scotchbond™ Etchant, 3M Espe, St Paul, MN), washed with water spray for 15 s and gently air-dried for 5 s. Dentin primer (Scotchbond Multi-Purpose Primer, 3M Espe) was applied and then lightly air-dried for 5 s. The procedure was followed by applying a thin layer of dentin adhesive (Scotchbond Multi-Purpose Adhesive, 3M Espe), which was then light-polymerized for 10 s, as suggested by the

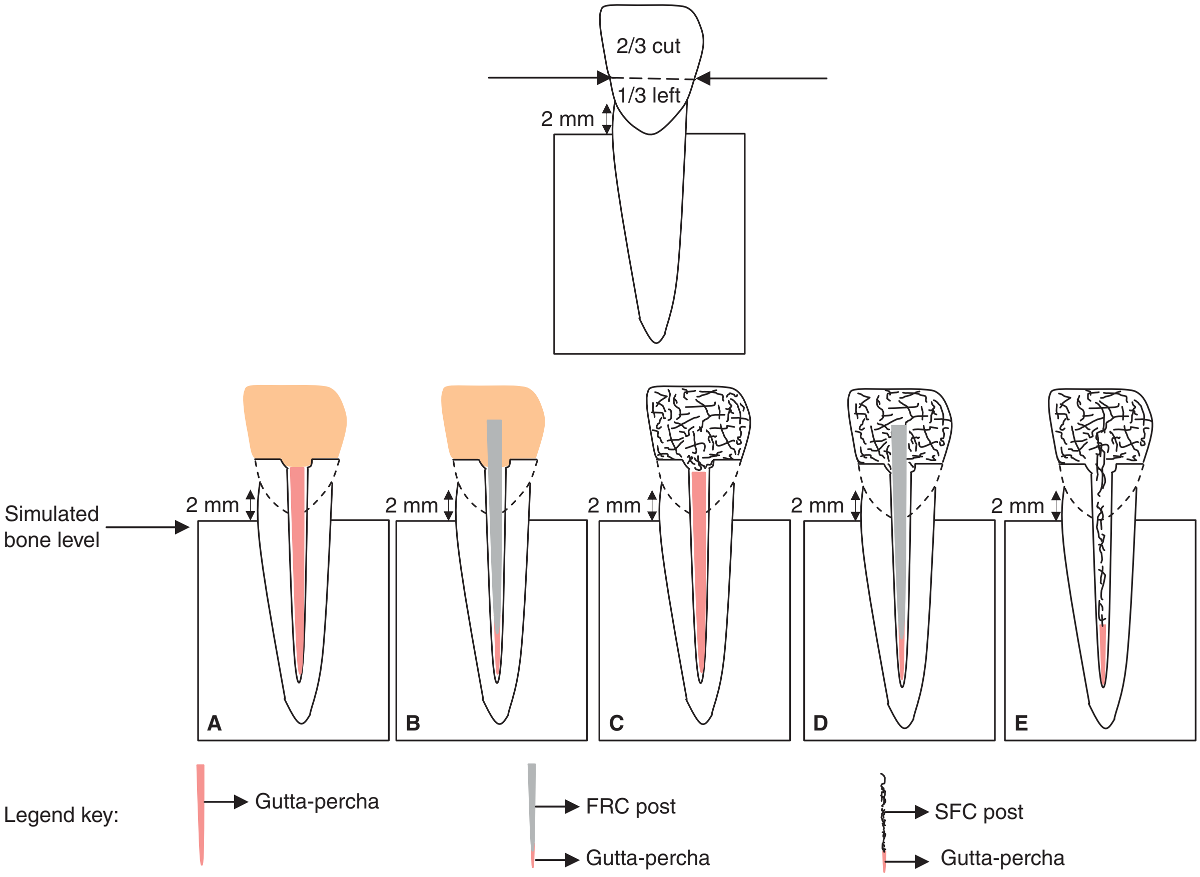

Figure 1. Schematic figure representing the test groups. Group A: Direct composite crown restorations from conventional composite (CC); Group B: FRC post (l = 14 mm; ø = 1.5 mm) and direct composite core-crown restorations from CC; Group C: Direct composite crown restorations from SFC; Group D: FRC post (l = 14 mm; ø = 1.5 mm) and direct composite core-crown restorations from SFC; Group E: Direct composite post-core-crown restorations from SFC.

manufacturer. In group A, conventional composite (CC) (Supreme, 3M Espe) was selected for fabricating the direct composite crown restorations while, in group C, SFC was used with the same purpose.

The coronal and middle third of each root canal was prepared with Gades-Glidden drills (Gates Glidden, Dentsplay Maillefer, Ballaigues, Switzerland), to number 4 under water cooling, leaving 3–5 mm of the root canal filling in the apical portion. The root canals were then sequentially enlarged up to 1.5 mm. This procedure standardized the post lengths and diameters in these groups with FRC post and SFC post reinforcement. The same operator instrumented all root canals to the same size.

The FRC posts (Groups B and D) with a semi-IPN polymer matrix are referred to as individually formed FRC posts and were fabricated filling up the whole post space with fibers from one fiber bundle of everStick (Stick Tech, Turku, Finland) with a length of 14 mm (equal to 2/3 of the length of the crown in the coronal part of the tooth) and diameter of 1.5 mm, following the manufacturer's instructions. First the bundle of pre-impregnated glass fibers was cut to a length of 14 mm, inserted into the root canal post space, both ends (the apical and coronal end) were fitted in, leaving 4 mm of fiber bundle above the coronal opening and then light-polymerized (Demi L.E.D., Kerr, Middleton, USA) with a wavelength with maximal intensity at 470 nm *in situ* for 20s. After it was removed from the root canal, the individually-formed FRC post was further light-polymerized for 40 s outside the canal. The surface of the FRC post was then wet with light-polymerizable dimethacrylate resin (Stick Resin, Stick Tech) for 5 min and protected from any light source by a lightproof box until cementation. The dentin surface in the root canal dentin and remaining coronal structure was etched, primed and adhesively treated as described above. A dual-curing composite resin luting cement (Para-Cem® Universal DC, Coltène/Whaledent, Altstätten, Switzerland) was mixed approximately for 20–30 s until an homogeneous paste was formed, by dispensing the base and the catalyst in a ratio of 1:1 on the mixed pat. Root canals were coated with the cement and a thin layer of this cement was also placed on the post surface before the insertion into the root canal. The individually-formed FRC posts were slowly seated into the root canals with slight finger pressure and the excess of cement was removed with an explorer. The coronal end of each post was positioned directly in contact with the tip of the light-curing unit and was light-polymerized for 40 s. The direct composite core and crown restorations were prepared as soon as the cement had hardened, ~ 4 min after cementation.

The SFC posts (Group E) were fabricated directly by condensing and polymerizing the short fiber composite resin incrementally into the root canals, until the coronal opening was achieved. A thin layer of short fiber composite with thickness of ~ 1 mm was first fitted into the root canal, condensed with suitable instrument and then light-polymerized. The tip of the light-curing unit was placed in direct contact with the coronal opening of the root canal and each increment was light-polymerized for 40 s. Since the SFC posts were formed by condensing and light-polymerizing each layer directly into the root canals, no cement was used as luting medium. Coronal restorations consisting of direct composite cores and crowns were prepared immediately after the SFC posts were light-polymerized.

Coronal restoration: Direct core and crown fabrication

The remaining dentin surface in the coronal part was covered either with CC or SFC, so that the first composite increment overlaid the entire preparation. Approximately three composite layers were needed to cover the coronal part of the FRC post (Groups B and D), therefore providing the direct composite core with a conical shape. This complex in Groups B and D counts as a direct post-core foundation. Also, three short fiber composite layers were incrementally placed, providing the direct composite core in Group E. Thus, the SFC post-core foundations were secured as well. Each composite layer, regardless of the group, was light-polymerized for 40 s.

In order to obtain ideally contoured direct composite crown restorations and to standardize the dimensions, a mould of transparent polyvinyl siloxane impression material was made (Memosil 2, Heraeus Kulzer, Germany). Depending on the group, CC or SFC was applied in three increments into the transparent mould, which was then placed on the tooth surface with slight pressure. After the excess was removed with a suitable instrument, each increment was light-polymerized from two sides for 20 s outside the mould. After the mould was removed, the composite increment was further light-cured for another 40 s (20 s per side). The light source was placed in close contact with the composite surface. All direct composite restorations were finished and polished with diamond burrs, white stones and diamond polishing cups under water cooling.

After finishing the restorative procedure, the teeth were mounted in the middle of an acrylic resin (Palapress, Heraeus Kulzer, Wehrheim, Germany) cylinder (diameter 20 mm, height ~ 15 mm) at a level of 2 mm below the lowest point of the simulated CEJ, simulating the bone level. During the entire procedure, the teeth were maintained in a wet environment and then stored in distilled water at 37°C for 5 days before testing.

Fracture load test and statistical analysis

The acrylic block containing the restored tooth was tightly fixed to the inclined metal base to provide a 45° angle between the palatal surface of the tooth and the loading tip (Figure 2). A static load until fracture was applied to the crowns 2 mm below the incisal edge on the palatal side (at a 45° angle), using a universal testing machine (Lloyd LRX, Lloyd Instruments Ltd, Fareham, UK) with a cross-head speed of 1.0 mm/min. The specimens were loaded until fracture with load values measured in Newtons (N). The load deflection curves were recorded with PC computer software (Nexygen, Lloyd Instruments Ltd, Fareham, UK) and were determined and analyzed after testing (Figure 3). The beginning of the specimen damage was classified as the initial fracture (IF) and the maximal load at which the final fracture appeared was classified as the final fracture (FF).

Differences regarding the failure mode among the groups were visually analyzed by two operators and divided into two groups according to the failure mode (Figure 4): favorable type (restorable) above the preparation line and above or at the simulated bone level (adhesional failure at bonding surface) which has the possibility to be repaired easily and the unfavorable type (non-restorable) below the simulated bone level (root fracture), which is difficult to repair.

Data of the fracture-load values were statistically analyzed with SPSS version 19 (Statistical Package for Social Science, SPSS Inc, Chicago, IL) using analysis of variance (ANOVA) followed by the Tukey's post-hoc test. The fracture types were analyzed with

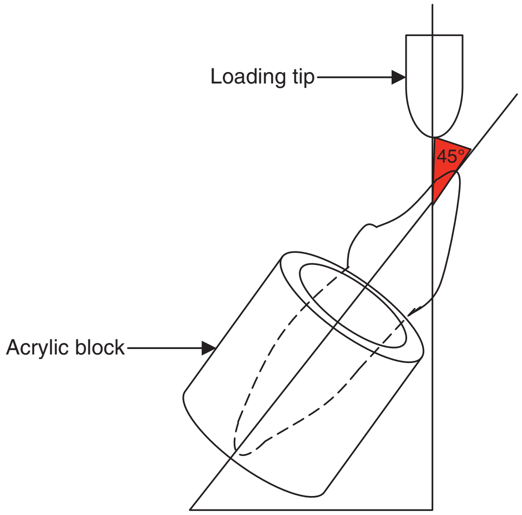

Figure 2. Schematic picture representing the testing set up.

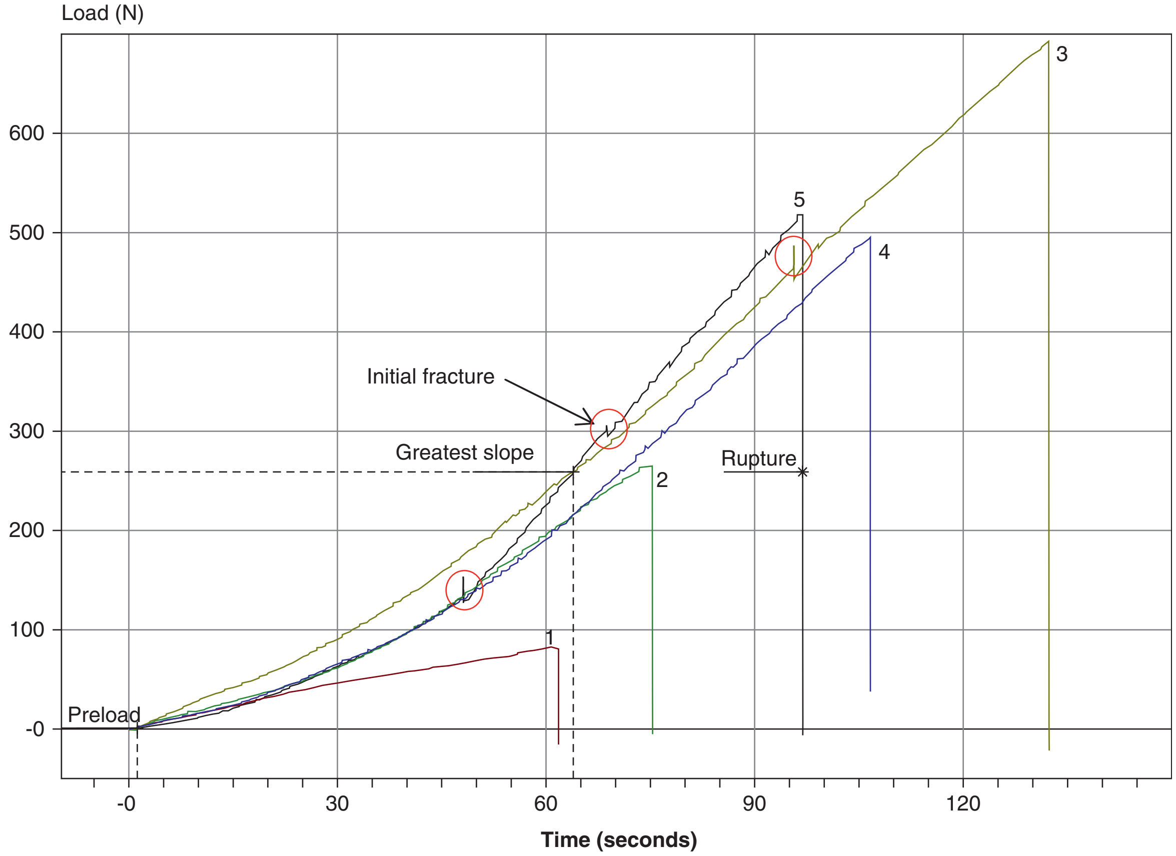

Figure 3. Load–deflection curves for tested groups. 1 (Group A); 2 (Group B); 3 (Group C); 4 (Group D) and 5 (Group E). The drops in the curves (circled peaks) are considered as initial fractures (IF). An example of the typical curve and designation of IF is shown with curve 5 for Group E.

chi-square test at a significance level of 0.05 to determine the differences among the groups.

Results

Table II summarizes the mean initial and final fracture load values with standard deviations (SD) for the test groups. The same initial and final fracture load values were recorded for the teeth restored with conventional composite, plain or with FRC post reinforcement. Final fracture load values for all SFC restored teeth differed from the initial fracture load values and tended to increase as the values of initial fracture load increased. ANOVA revealed that the restorations made from SFC gave the greatest final fracture load values when FRC post reinforcement was not included into the structure. The data demonstrate that SFC restorations additionally reinforced with SFC post-core foundations had higher load-bearing capacity than teeth restored with CC or

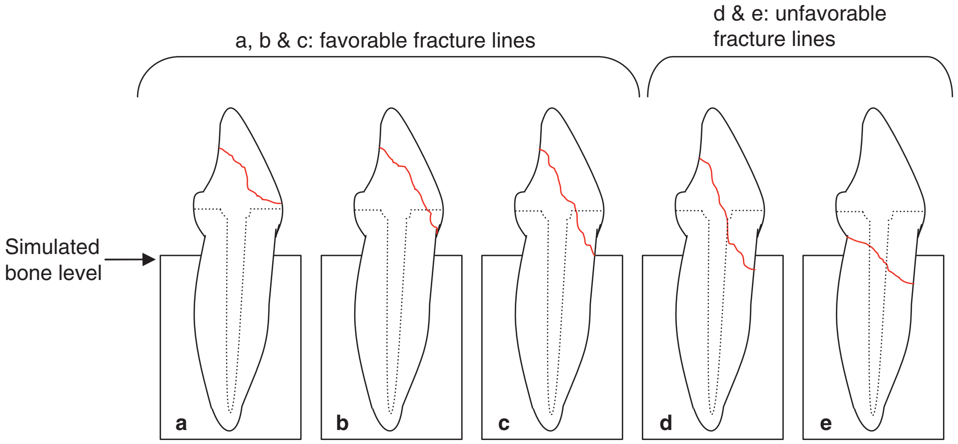

Figure 4. Schematic picture representing the fracture lines. The broken line represents the preparation line. The red line represents the fracture line.

Table II. Fracture load values and standard deviations (SD) of the tested groups.

Groups	Fracture load (N) Initial fracture	Final fracture
A (plain CC)	164.8^{a} (95.1)	164.8^{a} (95.1)
B (CC with FRC post)	296.0^{ab} (184.5)	296.0^{ab} (184.5)
C (plain SFC)	469.8^{b} (249.0)	515.8^{b} (241.6)
D (SFC with FRC post)	442.3^{ab} (169.3)	467.2^{ab} (156.8)
E (SFC with SFC post)	441.1^{ab} (245.1)	490.5^{b} (288.6)

The same superscript letter above the load values refers to an homogenous sub-set ($p > 0.05$, Tukey).

SFC both reinforced with FRC post, but lower than the restorations made with plane SFC. Initial and final fracture load values for restorations where SFC was reinforced with SFC post-core foundations did not statistically differ from the restorations made with plain SFC nor from the restorations where SFC was reinforced with FRC post. The control group, where plain CC was used as a restorative material, gave the weakest fracture load values.

Five types of fracture lines were observed (Figure 4). The first type of fracture line (a) starts and ends above the preparation line; the second type of fracture line (b) starts at the loading point on the palatal side, continues to the buccal side and ends above the simulated bone level; the third type of fracture line (c) starts at the loading point on the palatal side, continues to the buccal side and ends at the simulated bone level; the fourth type of fracture line (d) starts at the loading point on the palatal side, continues to the buccal side and ends below the simulated bone level; and the fifth type of fracture line (e) starts below the loading point, continues to the buccal side and ends below the simulated bone level. Fracture lines a, b and c are favorable fracture types, whereas the fracture lines d and e are unfavorable fracture types.

Fracture mode analysis indicated that the SFC post-core-crown restorations fractured in a more favorable mode than any other material used (Table III). However, the chi-square test revealed no significant statistical difference in the failure mode among the groups ($p > 0.05$).

Discussion

This study simulated a case of endodontically-treated maxillary central incisors with severely damaged crowns and minimal remaining dentin. The restoration of severely damaged ETT used in this study included individually-formed FRC posts with direct CC or SFC crown restorations or SFC posts with direct SFC crown restorations. In the groups with FRC post reinforcement, the fiber bundle was left 4 mm above the coronal opening, therefore providing a post-core foundation. Posts with a semi-IPN polymer matrix were individually formed from pre-impregnated continuous unidirectional E-glass fiber and were selected for this study because they have better adhesion to cement [13] and may enhance the adhesion to composite core [17]. The advantage of the E-glass fiber with a semi-IPN polymer matrix is the ability to take the shape of the post space, therefore showing properties of a highly adjustable system and giving the opportunity to fabricate the post as the same as possible for each specimen. In the group with SFC post reinforcement, the SFC served as a post-core foundation and direct composite crown restoration. Control groups did not include post placement. The crowns were only restored either with plain CC or plain SFC. All crown designs in this study were attempted to simulate a direct technique, since studies have shown that direct composite resin is a promising alternative to conventional treatment modalities [24,25]. Still, the use of restorative composite resins in high stress-bearing applications such as direct crown restorations for endodontically-treated roots remains controversial, due to the fact that the fracture of the restorative composite resin is reported as reason for failure [26]. On the other hand, promising results are documented with the SFC as the core and direct composite crown material [21–23], which may indicate that root filled teeth in some instance can be restored without conventional crown coverage.

The restorations made from SFC without any reinforcement gave the greatest fracture load values in this study (Table II). Placement of the FRC post had an effect on the fracture load of restorations restored with CC, but not with SFC. The composition of the restorative composites used in the present study could explain the results. The short fibers have random, three dimensional orientation, whereas unidirectional fibers have a continuous direction in one dimension. Unidirectional fibers give superior strength compared to short fibers, but only when the direction of stress is the same as that of the direction of the fibers [14]. Therefore, the effect of FRC post on the CC could be

Table III. Failure mode distribution of test specimens in percentages (%).

Group	Favorable fractures	Unfavorable fractures
A (plain CC)	49%	51%
B (CC with FRC post)	51%	49%
C (plain SFC)	37%	63%
D (SFC with FRC post)	50%	50%
E (SFC with SFC post)	63%	37%

CC, conventional composite; FRC post, fiber reinforced composite post; SFC, short fiber composite; SFC post, short fiber composite post.

firstly due to the longitudinal orientation of the unidirectional fibers in the individually-formed FRC post providing an anisotropic reinforcement to the direction of the load and, secondly, due to the stress transfer from the polymer matrix to the fibers, preventing the tooth fracture. Fibers absorbed the stress and this additionally resulted in a favorable failure mode indicating that the FRC root canal post was the load-bearing component of the root-canal-post system. The dental construction with E-glass fiber post is composed of individually-formed FRC post, resin composite cement, dentin, core and crown build-up resin composite, with the FRC post as a load-bearing component of the structure. All materials need to have similar strength and adhesive compatibility so the functional stress transmission would be effective. This type of dental construction has a multiphase nature, whereas SFC post dental construction consists basically of dentin and short fiber composite, since the post and the core-crown material is identically the same. The fracture failures with an individually formed FRC post are reported to be mainly cohesive with only a few adhesive or mixed fractures observed [13], which may lead to interface debonding and restoration failing. Therefore, the bonding quality between post and resin cement-dentin, the homogeneity and integration among the materials (dentin, post, luting medium and core composite) are important parameters for the clinical performance and longevity of the individually formed FRC post system. As reported, posts with inter-diffusion bonding may form a root-post system in which debonding stress is more evenly distributed with less shear stress forming at the inter-phase of dentin and post [13]. This differs from the mechanism that occurs with SFC construction, where individual short fiber acts as a crack stopper and arrests the fracture transmission to the adjacent individual short fiber. According to the results of the present study, SFC exceeded the reinforcing effect of the FRC post used with conventional or short fiber composite, but only when used to restore teeth with direct crown restorations without post space preparation. SFC consisting of randomly orientated short E-glass fibers provides an isotropic reinforcement effect in multi-directions instead of one direction [27]. This contributes to re-distributing the stress to a broader surface, increasing the load threshold at which the restorative material begins to micro-crack, therefore withstanding greater load values. When the post was included into the structure, there was no statistical difference between the reinforcement efficiency provided by FRC post or SFC post, but the SFC post reinforcement resulted in more favorable failures (63%). The isotropic nature of SFC and the stress distribution could explain the reinforcement efficiency of the SFC. The results of the present study are in agreement with Garoushi et al. [21], who reported improved load-bearing capacity of the short fiber composite compared to CC and any combination of the material used, and of SFC resin post-core restorations compared to CC core restorations reinforced with fiber post [22]. Another study reported enhanced capacity of the SFC restorations to sustain the load, compared to CC restored teeth with or without FRC reinforcement [23].

Local failures or internal damages often occur in the resin composite before the final catastrophic fracture. The beginning of specimen damage in this study was classified as the initial fracture (IF) describing the damage initiation (beginning of fracture; initial fracture). After initial fracture, damage may accumulate slowly or progress rapidly and fiber orientation and position are important determinants to initial and final fracture [28]. The teeth with direct CC crown restorations, with or without FRC posts, fractured in an instant at the final load, showing no difference between initial and final fracture load values (Table II and Figure 3). SFC restored teeth evaluated initial fracture load values always lower than the final fracture load values. Due to the fiber orientation, SFC appeared to slow the fracture process that began at lower load values, which minimized the instantaneous failures. This might be additionally related to the gradual breakage of the fibers, resulting in a rather more gradual than sudden drop of the loading force, as described earlier [29]. The values of the final fracture loads increased as the values of the initial fracture loads increased. Consequently, initial fracture load values can be used as indicators to predict the final fracture load [28,29].

It was hypothesized that restorations made from composite resin reinforced with short E-glass fiber filler with a semi-IPN-polymer matrix (SFC) as a dental material of choice for both the post-core foundations and the direct composite crown restorations can sustain the load required for a direct post-core-crown-complex. The results of the present study supported the hypotheses. Severely damaged maxillary incisors restored with SFC crown restorations additionally reinforced with SFC post-core foundations gave fracture load values statistically not different from the control specimens, where SFC was used alone to restore teeth with direct crown restorations without post space preparation, but fractured favorably in a greater percentage (63%) than the teeth restored with any other material combination used. This is due to the isotropic nature of the short fiber; the reinforcing fibers in SFC are short random-oriented fibers with semi-IPN-polymer matrix having both cross-linked polymer formed from dimethacrylate resins and the linear polymer PMMA mixed together. If the reinforcing effect of the fibers is divided in several directions as is the case with SFC, the maximum strength values are considerably lower, but the toughness of the material is increased. Composites such as SFC that have randomly orientated fibers are isotropic (not direction dependent) in their mechanical and physical properties and the length and adhesion of fibers should provide load transfer from the polymer matrix to the fibers. The length is important for achieving the maximum reinforcing effect, which is possible if the fibers have a length equal or greater than the critical fiber length [18], whereas initially poor adhesion between the fibers and polymer matrix increase the critical fiber length. The length of 3 mm was chosen for the SFC since previously no difference was found in the load-bearing capacity provided by fibers of 2–5 mm [27] and the use of 3 mm long fibers resulted with composite with good handling properties. On the other hand, the longer the fibers are the bigger is the possibility of changing the orientation of fibers from random to one direction. Due to the identically same material used, homogenous units were secured between the post-core foundations when teeth were restored with SFC direct crowns and SFC posts. Because of the multi-directional fiber orientation at the interface between the post-core and the root dentin as well as between the post-core and the crown restoration, the stress transferred at the root-crown area resulting in fractures that ended above or at the simulated bone level (fracture lines b & c respectively) or even above the preparation line (fracture line a) (Figure 4). The reinforcing effect of the fiber fillers is based on stress transfer from the polymer matrix to the fibers and also on the behavior of individual fiber as a crack stopper. Due to this, SFC has an ability to eliminate or arrest crack propagation, which might contribute to a higher rate of favorable mode of failure. Within the limitations of this study, it can be, therefore, suggested that reinforcing severely damaged endodontically-treated maxillary central incisors with SFC resin post-core foundations and direct SFC crown restorations may lead to better tooth performance than if restored either with CC or SFC direct crowns reinforced with FRC posts.

There are a few limitations of this study. Embedding the roots directly into the acrylic blocks might have provided external reinforcement to the root structure by the rigid acrylic resin, altering the strengths of the roots. Providing a periodontal ligament could minimize this limitation. The load was applied to a single point until fracture in contrast to the *in vivo* situation, where loads are applied repeatedly over a long period. The clinical crowns of all teeth included in the study were flattened and the coronal structure representing the ferrule was not prepared. The ferrule might have contributed to reinforcing the cervical area and, consequently, changing the failure mode. One previous study investigated the effect of a ferrule with SFC and suggested that anterior teeth with 2 mm ferrule restored with a SFC post-core complex would resist normal occlusal forces [22]. The effect of the 2 mm ferrule was also studied with a FRC post-SFC crown restoration complex, demonstrating the importance of a ferrule in reinforcing the cervical area [23]. This study design simulated a case of severely damaged anterior teeth with a flattened surface remaining and without the possibility for a ferrule preparation. In this study, the loss of tooth structure was not associated with the access preparation. With the minimally remaining coronal structure, the teeth in the present study were strengthened either with individually formed FRC posts or SFC posts. In the first case the fiber bundles were extended 4 mm above the coronal surface of the prepared teeth, simulating, therefore, a ferrule effect. In the case with SFC posts this phenomenon was absent, but the posts and cores were fabricated from the identically same restorative material, which is beneficial from two aspects: the capability of transmitting the functional stress is the same and it insures more a homogenous unit formation between the post and the core with short fibers orientated in multi-directions. It should be emphasized that this is not a substitute for a ferrule, but contributes to strengthening the cervical area, as occurs with a ferrule. However, clinical trials are necessary to evaluate the clinical performance and the survival probability of SFC in dental restorations with and without a ferrule design *in vivo*. Thermocycling was not performed, so moisture and temperature changes encountered in the mouth were not simulated. On the other hand, all teeth in the present study were restored with direct composite crown restorations as occurs in clinical practice, which might have given more reliable results. Endodontic posts provided by the coronal part clinically are protected from contamination in the oral environment. In the present study all posts were placed in endodontically-treated maxillary incisors and their coronal parts were immersed into the composite cores and crowns. Posts were not directly exposed to water contact. This condition is very similar to that in a clinical situation and is not followed by the reduction of the flexural strength as a consequence of the contact of a post with water [30]. A 5 day period of water storage at 37°C in distilled water was considered as a sufficient duration time for aging the restorative materials, due to the fact that their highest tendency to decrease in strength [31] and the maximal water sorption [32,33] were earlier observed between the 1 and 7 day immersion time, i.e. the first week. Water storage decreases the flexural strength of the SFC by an average of 20% [34]. Large restorations as found in this study are difficult to complete with a single layer of composite resin and have to be built-up incrementally with two or more layers. In order to secure the optimum bond to the remaining dentin in the coronal part, care was taken to cover the entire preparation with the first increment of composite resin.

The authors of this study emphasize that the use of the composite resin reinforced with short E-glass fiber filler with a semi-IPN-polymer matrix as a dental material of choice for both the post-core foundation and the direct composite crown restoration is not a substitute for conventional treatment methods. Within the limitations of this study it can be suggested that the use of an adhesive technique and short fiber composite resin for both the direct composite post-core and crown material may offer one alternative method to conventional treatment modalities for restoring severely damaged incisors.

Superior adaptation of the SFC restorative material and the multi-directional fiber orientation at the interface between the post-core and the crown as well as between the post-core and the root dentin may be a supportive factor which eliminates or arrests crack propagation.

In conclusion, the use of SFC as a restorative material of choice for fabricating the direct composite post-core-crown restorations of severely damaged incisors provided an improved load-bearing capacity greater than CC used plain or with FRC post reinforcement. When post was included into the structure with SFC crown restorations, there was no difference between the reinforcement efficiency provided by FRC post or SFC post. Due to the lack of statistical difference between them, it can be concluded that with both post reinforcement types tooth structure was preserved (Group D 50%, Group E 63%) and fracture patterns most likely would favor a re-treatment of fractured specimens. This anyhow needs further investigations and this question will be evaluated in future studies.

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