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Influence of Fiber Type on Fatigue Performance of Fiber-Reinforced Inlay-Retained Dental Prostheses

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ABSTRACT

Objectives: To assess the effect of using only long- and short-glass fibers or their combination on the fatigue resistance of composite inlay-retained dental prostheses in dissected mandibular molars with different levels of periodontal support.

Materials and Methods: Seventy-two mandibular first molars and second premolars were included in our study. Distal halves of extracted molars were kept, and received endodontic treatment. Standardized occluso-distal and mesio-occlusal cavities were prepared, and premolar-molar units were assembled. The edentulous spans were restored by direct inlay-retained composite prostheses fabricated in 3 different ways (n = 12, 6 groups). In groups 1A and 1B, long fibers and a packable composite, in groups 3A and 3B, short fibers, while in groups 2A and 2B both short and long fibers were used. All units were embedded simulating either physiological periodontal support (1A-3A) or furcation involvement (1B-3B). Specimens were subjected to accelerated fatigue-testing through 40,000 cycles or until fracture. Kaplan–Meyer survival analysis and factorial ANOVA were conducted. Fracture mode was evaluated visually and by scanning electron microscopy.

Results: Group 2A (mean 39106.00 N, SD ± 2451, survival frequency 83.3%) and 2B (mean 38454.33 N, SD ± 3110, survival frequency 75%) had the highest load-bearing capacity. Factorial ANOVA revealed that the restorative material significantly affected load-bearing capacity ($P < .05$) regardless of the periodontal support.

Conclusion: The combination of long and short fiber-reinforced systems significantly enhanced the fatigue resistance of direct inlay-retained composite prosthesis.

Clinical relevance: This approach may counterbalance the weakening effects of impaired periodontal support, thus improving treatment outcomes for patients with compromised molar support.

Introduction

Permanent molar teeth play an essential role in mastication, as they bear a considerable portion of the occlusal load.[1,2] However, their early eruption, unique anatomy, and posterior

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position in the arch[3-5] make them more prone to cariological, endodontic, and periodontal diseases[6-9] compromising their long-term survival.[9-15] If a lesion is restricted to one root, hemisection can be an alternative to tooth extraction.[16-18] Retaining the relatively intact part of the tooth helps to preserve the natural tooth structure and the surrounding alveolar bone, and it may also facilitate the placement of a fixed prosthesis in cases where regenerative periodontal surgery or implant placement are relatively contraindicated.[19] Hemisection may be indicated in cases of advanced furcation involvement, root fractures or perforations, untreatable apical lesions, severe root decay or resorption, and bone dehiscence affecting a single root.[20]

While dental implants remain a standard solution for substituting posterior missing teeth,[21] they are not always ideal due to anatomical, medical, or financial limitations – particularly in periodontally compromised patients.[22-24] In such cases, hemisection combined with conservative prosthetic rehabilitation offers a less invasive, cost-effective, and repairable alternative. Numerous clinical studies have reported favorable long-term outcomes for root-resective therapy, with survival rates reaching 93% over 10 years[25] and also a systematic review showing 5-10-year survival rates between 38% and 94.4% depending on case selection.[26] Rasperini and colleagues have clearly suggested the option of hemisection or root resection in periodontal treatment of different fircation involvements.[27] However, teeth undergoing such therapy require special restorative or prosthetic care.

Intracoronally retained fiber-reinforced composite prostheses can be a suitable option for such cases as they maximize the preservation of remaining tooth structure while stabilizing the involved teeth simultaneously.[28,29] A clinically relevant and frequent situation is when the mesial half of a mandibular molar is resected due to cariological, endodontic, or periodontal reasons. Several factors make the distal tooth half more favorable to retain. Firstly, the mesial marginal ridge is more prone to carious lesions than the distal,[30] as the distal contact surface is smaller, and the absence of an adjacent wisdom tooth makes it a self-cleaning area. Secondly, the mesial root usually curves distally and contains two root canals with a complex anastomosis system between them, making endodontic treatment more challenging.[31-35] Moreover, it may present a deep concavity distally, increasing the risk of strip perforation and complicating plaque control procedures, which can result in persistent periodontal inflammation. In contrast, the distal root has an oval cross-section with usually one wide root canal and a greater bulk of dentine, making endodontic treatment, preparation, and restoration much easier.[36] After hemisection and endodontic treatment of the distal root, the edentulous span can be restored with an intracoronally retained prosthesis using different types of fiber-reinforced composite materials.

Despite the increasing amount of evidence supporting the use of fiber-reinforced direct and indirect composite prosthesis for more extensive defects,[37-39] limited information is available on their longevity and clinical performance in restoring hemisected mandibular molars. Typically, continuous fibers are used for the reinforcement of inlay-retained composite prostheses. However, discontinuous, short fiber-reinforced composite (SFRC) materials have recently been utilized successfully for various other restorative purposes.[29] There is a limited availability of literature data on the performance of different fiber-reinforcement solutions for fabricating direct inlay-retained dental prostheses under varying conditions of periodontal support.

The aim of this study was to evaluate the benefit of using long continuous fibers, short discontinuous fibers, and their combination in reinforcing direct composite prostheses, focusing on their impact on fatigue resistance and fracture patterns. Assessing the impact of periodontal support on fracture resistance and fracture patterns was another objective of the study.

The null hypotheses were that there would be no difference between the test groups in either (1) fatigue resistance or (2) fracture patterns.

Materials and methods

Specimen selection

Seventy mandibular second premolars and seventy mandibular first molars were selected and included in the study. All teeth had been extracted previously due to periodontal or orthodontic reasons and were used within six months of extraction. Soft tissue residues, cementum, and calculus covering the root surfaces were removed with hand and ultrasonic scalers, and the teeth were stored in 0.9% saline solution at room temperature until use.

The primary inclusion criteria were as follows: the visual absence of caries, root cracks, previous endodontic treatment, posts or crowns, or resorptions. Regarding the coronal dimensions of the molar teeth, approximately 90% of the specimens ranged from 10 to 10.9 mm in the bucco-lingual dimension, with the remaining specimens measuring between 11 and 12 mm. The mesio-distal dimension of the specimens was also measured; a mean was calculated, and only specimens within $\pm$10% of the mean were included. The height of the specimens, measured from the cemento-enamel junction (CEJ), ranged between 8 and 9 mm. The length of the distal roots was between 14 and 16 mm. As for the coronal dimensions of the premolars, 90% of the teeth measured between 9 and 10 mm in the bucco-lingual dimension. In terms of mesio-distal dimension, 90% of the specimens measured between 7 and 7.5 mm.[40]

Specimen preparation

All procedures were performed by the same operators. The mandibular first molars were sectioned along the oro-vestibular bisector of the crown with a vertical cut, and only the distal halves of the teeth, with intact buccal, distal, and lingual walls, were retained for further procedures.

The sectioned surfaces were finished and polished to create a cleansable, nonretentive surface. In the hemisected distal tooth halves, the pulp chambers were deroofed, and endodontic treatment of the distal canal(s) was performed. The root canals were instrumented with Pathfiles (1-2-3) and ProTaper (S1-S2-F1-F2-F3) (Dentsply Maillefer) and were irrigated by 5% NaOCl alternating with 10% EDTA (ethylenediaminetetraacetic acid). The root canal filling was performed by

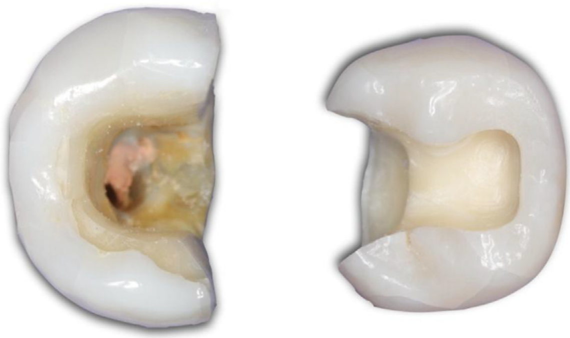

Figure 1 – In premolars, standardized occluso-distal (OD) cavities were prepared, while mesio-occlusal (MO) cavities were created in the hemisected distal tooth halves.

matched-single-cone obturation with a master cone matching the final instrument used for preparation and sealer (AH plus; Dentsply Maillefer). In all premolars, occluso-distal (OD) cavities were prepared, while in the hemisected distal tooth halves, mesio-occlusal (MO) cavities were created (Figure 1). Cavities were prepared as follows:

- Proximal box width was set to two-thirds of the tooth's bucco-lingual width.
- Occlusal isthmus width was set at half the bucco-lingual width.
- Isthmus depth was prepared 3.5 mm from the tip of the lingual cusp.
- Cervical cavity margin was set to be 1 mm above the CEJ.
- Cavosurface margins were cut at 90°, with rounded internal line angles. Parallel buccal and lingual walls were prepared to ensure consistency.[41]

All specimens received the same adhesive treatment. The pulp chambers of the dissected molars and the proximal boxes of the premolars were roughened, cleaned, and, following selective enamel etching for 15 seconds with 37% orthophosphoric acid, a one-step self-etch adhesive system (G-Premio Bond, GC Europe) was applied according to the manufacturer's instructions. The adhesive was photopolymerized for 40 seconds. The average power density of the light source, measured with a digital radiometer (Jetlite light tester; J. Morita USA Inc.,) before the bonding procedure, was 840 ± 26.8 mW/cm^2. After light-curing, the proximal boxes and pulp chambers were filled up to the level of the occluso-pulpal wall with a composite filling material (G-aenial Posterior A3, GC Europe) and light-cured for 20 seconds.

Direct prosthesis fabrication

All the specimens were prepared in the same manner, regardless of the different restorative materials that were later used for the inlay-retained prostheses. First, the premolars and dissected molars were paired to form 72 restorative units. To facilitate the removal and repositioning of the pairs during the subsequent restorative procedures, a light body silicone impression material was used to secure them in a gypsum block (Figure 2A). A transparent silicone index was

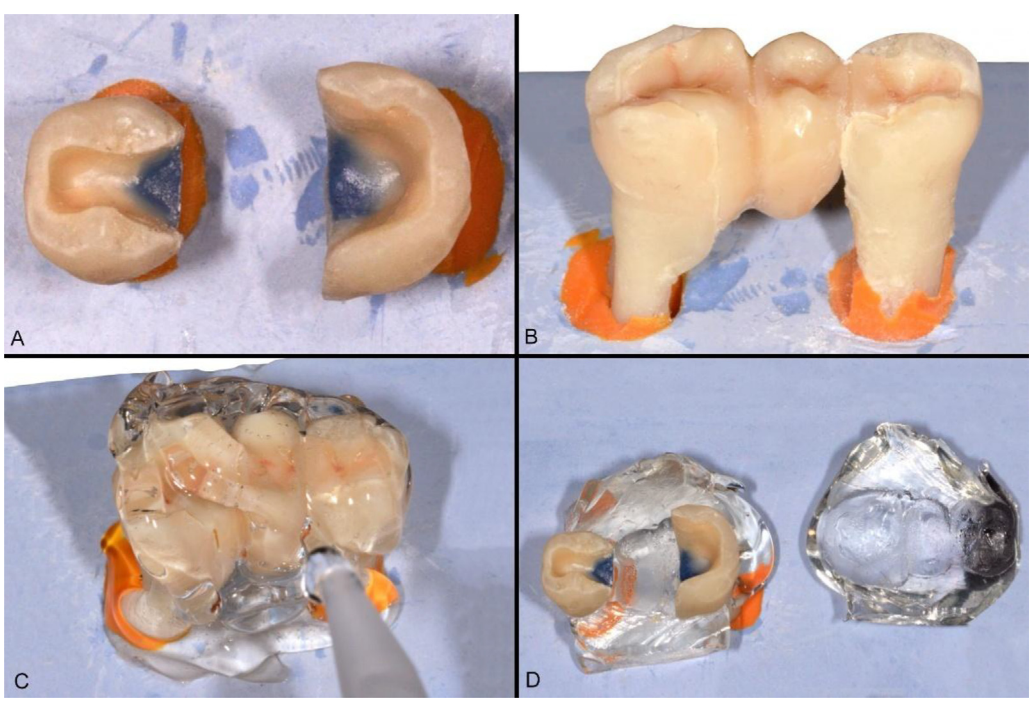

Figure 2 – A standardized, transparent silicone index aided the fabrication of the direct, inlay-retained dental prostheses. A, Light body silicone impression material was used to secure the teeth in a gypsum block. B, An inlay-retained composite prosthesisfabricated by a laboratory technician and placed into the cavities of each unit. C, A transparent silicone impression material (Exaclear, GC Europe) used to fabricate a silicone index for the future prosthesis. D, The silicone index was then sectioned horizontally at the equator, and the prosthesis was removed.

Table 1 – In Group 1, continuous unidirectional glass fibers were used; in Group 3, only discontinuous short fibers (SFRC) were applied; and in Group 2, both continuous and discontinuous short glass fibers were utilized during the restorative procedure.

	Group 1	Group 2	Group 3
Pontic base	G-aenial Posterior	EverX flow dentin shade (SFRC)	EverX flow dentin shade (SFRC)
Central glass fibers	G-aenial Universal flow, everStick C&B (continuous fibers)	everStick C&B (continuous fibers)	EverX flow dentin shade (SFRC)
			
Occlusal covering layer	G-aenial Posterior	EverX flow dentin shade (SFRC)	EverX flow dentin shade (SFRC)

individually created for each specimen to standardize the size and shape of the direct, inlay-retained prostheses. The following protocol was applied: a prefabricated, inlay-retained composite prosthesis was fabricated by a laboratory technician and placed into the cavities of each unit (Figure 2B). All potential gaps were sealed with temporary filling material, and a template was made from a transparent silicone impression material (Exaclear, GC Europe) to create a silicone index for the future prosthesis (Figure 2C). The silicone index was then sectioned horizontally at the equator, and the prosthesis was removed (Figure 2D).

Table 1 summarizes the different FRC materials that were utilized for the fabrication of the inlay-retained dental prostheses.

Three groups (Group 1-3, n = 24/group) were created based on the restorative materials used, as follows:

- *Group 1*: packable microhybrid composite (Gaenial Posterior A3) was molded to the horizontally cut silicone index to form the gingival part of the pontic up to the level of the occlusal boxes of the teeth and photopolymerized for 40 seconds. A highly filled flowable composite (Gaenial Universal Flow A3, GC Europe) was then applied to the walls of the prepared cavities, covering the cervical third of the box. Subsequently, a bundle of long, unidirectional FRC (everStick C&B, GC Europe) was used as the prosthesis framework.[42] It was cut to the appropriate length, positioned, and photopolymerized. The remaining occlusal two-thirds of the inlay-retained dental prosthesis was molded using the same packable composite (Gaenial Posterior A3), and the final occlusal layer was photopolymerized for 40 seconds through the transparent silicone index to standardize the occlusal anatomy. The prostheses were then finished using fine granular diamond burs (FG 7406-018, Jet Diamonds, and FG 249-F012) and polished with aluminum oxide polishers (OneGloss PS Midi, Shofu Dental GmbH) (Figure 3A and B).
- *Group 2*: Flowable SFRC (EverX Flow Dentin Shade, GC Europe) was molded to the horizontally cut silicone index to form the gingival part of the pontic, up to the level of the occlusal boxes of the teeth, and photopolymerized for 40 seconds. The same flowable SFRC was then applied to the walls of the prepared cavities, covering the cervical third of the box. A bundle of long, unidirectional FRC (everStick C&B) was cut to the appropriate length, placed in position, and photopolymerized, as done in Group 1. The remaining occlusal two-thirds of the inlay-retained dental prosthesis was again molded using the flowable SFRC, and the final occlusal layer was photopolymerized for 40 seconds through the transparent silicone index to standardize the occlusal anatomy. The prostheses were finished and polished in the same manner as in Group 1 (Figure 3C and D).

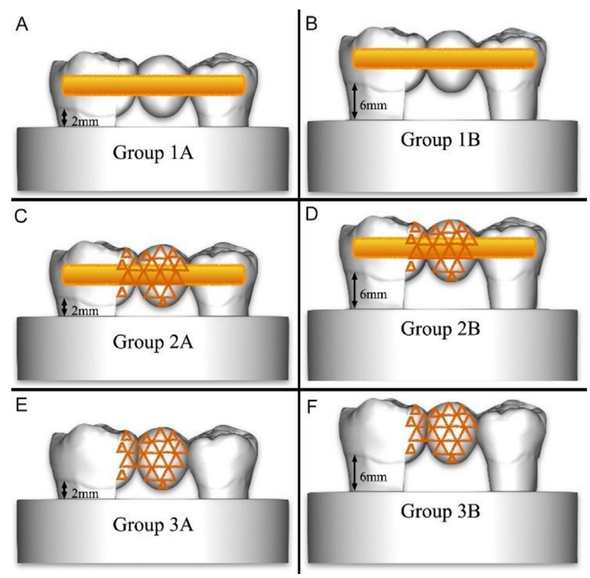

Figure 3 – Schematic representations of the six study groups. A and B, Group 1A and 1B: long fibers and a packable composite were utilized. 1A (A) simulates physiological periodontal support, 1B (B) simulates compromised periodontal support and furcation involvement. C and D, Group 2A and 2B Both short and long fibers were utilized. 2A (C) simulates physiological periodontal support, 2B (D) simulates compromised periodontal support and furcation involvement. E and F, Group 3A and 3B only short fibers were utilized. 3A (E) simulates physiological periodontal support, 3B (F) simulates compromised periodontal support and furcation involvement.

- *Group 3*: The direct composite prostheses were made entirely of flowable SFRC (EverX Flow Dentin Shade), without any long FRC reinforcement.[43] The clear silicone indexes were created in the same manner as described earlier, but instead of a horizontal cut, three holes were punched through the index, allowing the tip of the flowable SFRC to be inserted and the inlay-retained dental prosthesis to be molded. After the adhesive treatment of the cavities (as described above), the negative space encapsulated by the clear silicone index was filled incrementally with the flowable SFRC. Photopolymerization was performed through the transparent silicone index, with each layer light-cured for 40 seconds. The prostheses were finished and polished in the same way as in Groups 1 and 2 (Figure 3E and F).

Embedding of the specimens

All restored units were stored in saline 0.9% saline solution at room temperature before being embedded in a special methacrylate resin (Technovit 4004, Heraeus-Kulzer). Each group was divided into two subgroups (n = 12): in Groups 1A-3A, the specimens were embedded 2 mm from the CEJ to simulate intact periodontal conditions, while in Groups 1B-3B, embedding was performed 6 mm apical to the CEJ, representing furcation involvement.[40,44] The simulation of periodontal ligaments was achieved by applying a single layer of latex separating liquid (Rubber-Sep, Kerr) to the roots prior to embedding, according to the planned embedding level.[40,45] The six study groups and their corresponding levels of embedding are shown in Figure 3.

Mechanical testing

The specimens were subjected to an accelerated fatigue-testing protocol,[40,46] performed with an electrodynamic testing machine (Instron ElektroPlus E3000, Norwood). Cyclic isometric loading was applied using a 5 mm wide, round-ended metallic tip positioned at the distal fossa and the distal marginal ridge of the restored pontic. Initially, a cyclic load was applied at a frequency of 5 Hz as preloading. The load was then continuously increased to 100 N over 5 seconds, followed by dynamic loading at 100 N for 5000 cycles. Afterward, the load was increased by 100 N increments, with 5000 cycles completed for each increment, up to a maximum of 800 N. The teeth were loaded for a total of 40,000 cycles or until fracture occurred.

Scanning electron microscopy analysis

Representative specimens were examined using scanning electron microscopy (SEM; LEO). Before imaging, all sectioned samples were cleaned with alcohol and gold-coated using a sputter coater (BAL-TEC SCD 050, Balzers) under vacuum conditions.

Statistical analysis

Descriptive statistics were applied to summarize the data on survival for each group, providing information such as the mean, standard deviation, median, minimum, and maximum number of survived cycles. Survival frequency analysis was performed to show the count and percentage of items that survived or failed within each group. Univariate analysis of variance was conducted to assess the main effects of material and periodontal status on the number of cycles, as well as to examine whether there was a significant interaction between these two factors. This method helped in determining whether the differences in cycles were statistically significant. Finally, Tukey's HSD posthoc test was used after the ANOVA to compare the means of the different levels of material and identify specific pairs of materials that significantly differed in terms of their effect on the number of survived cycles. Data were tested for normality (Shapiro–Wilk test) and homogeneity of variances (Levene's test) before conducting ANOVA, and the assumptions were met.

Results

The descriptive statistics showed variation in the number of cycles across the different groups. For group 1A, the mean number of cycles was 32.568.17 (SD = 8626), with a median of 35.208, a minimum of 15.054, and a maximum of 40.000. Group 1B had a mean of 33.268 (SD = 6.395), a median of 35.925, with a minimum of 20.789 and a maximum of 40.000. Group 2A showed the highest mean number of cycles at 39.106 (SD = 2.451), with a median of 40.000, a minimum of 31.621, and a maximum of 40.000. In group 2B, the mean was 38.454 (SD = 3.110), with a median of 40.000, a minimum of 31.688, and a maximum of 40.000. Group 3A had a mean of 34.458 (SD = 7.056), a median of 37.000, with a minimum of 19.815 and a maximum of 40.000. Lastly, group 3B had a mean of 33.331 (SD = 6.572), a median of 35.261, a minimum of 20.158, and a maximum of 40.000. These findings are summarized in Table 2.

The survival frequency analysis indicated that in group 1A, 50.0% survived and 50.0% failed, while in group 1B, 25.0% survived and 75.0% failed. In group 2A, 83.3% survived and 16.7% failed, while in group 2B, 75.0% survived and 25.0% failed. Group 3A had a survival rate of 45.5%, with 54.5% failing, and group 3B had 27.3% surviving and 72.7% failing. This is also summarized in Table 2.

The univariate analysis of variance (ANOVA) revealed a significant main effect of material on the number of cycles, $F(2.45) = 6.342$, $P = .003$. There was no significant main effect of periodontal status, $F(1.45) = 0.061$, $P = .806$, and the interaction between material and periodontal status was also nonsignificant, $F(2.45) = 0.141$, $P = .868$.

The posthoc Tukey HSD test showed that the difference between groups 1 and 2 was significant, with a mean difference of 5861.87 cycles ($P = .004$). The difference between groups 2 and material 3 was also significant, with a mean difference of 4885.26 cycles ($P = .023$). No significant difference was found between groups 1 and 3, with a mean difference of 976.62 cycles ($P = .850$).

A posthoc power analysis was performed for the main effect of material in the factorial ANOVA. It was based on the observed effect size derived from the ANOVA table: partial $\eta^2 = 0.159$ for the Material factor, corresponding to $f = 0.43$

Table 2 – Descriptive statistics of the survived cycles.

Group	N	Mean	SD	Median	Minimum	Maximum	Survival % (count)
1A	12	32.568.17	8626.948	35.208	15.054	40.000	50.0% (6)
1B	12	33.268.42	6395.691	35.925	20.789	40.000	25.0% (3)
2A	12	39.106.00	2451.986	40.000	31.621	40.000	83.3% (10)
2B	12	38.454.33	3110.879	40.000	31.688	40.000	75.0% (9)
3A	11	34.458.36	7056.319	37.000	19.815	40.000	45.5% (5)
3B	11	33.331.45	6572.780	35.261	20.158	40.000	27.3% (3)

(medium-to-large effect). The total sample size included in this comparison was N = 70 specimens (24, 24, and 22 for the three material groups, respectively). Using α = 0.05, three groups, and f = 0.43 in a fixed-effects one-way ANOVA model, the achieved statistical power (1-β) was estimated in G*Power 3.1 (Universität Düsseldorf). The power was high (1-β = 0.89), indicating that the study was adequately powered to detect the observed difference between materials. By contrast, the interaction term (Material × Perio status) exhibited a negligible effect size (F = 0.14), implying that the current sample size was underpowered to detect such a small interaction effect.

In conclusion, the fiber reinforcement material used significantly affected the number of cycles, with Group 2 (long fiber + SFRC) performing better than both Groups 1 and 3. No significant effects were observed for periodontal status or the interaction between the material type and periodontal status. This conclusion is further supported by the Kaplan–Meier plots of the groups, as shown in Figure 4.

In the visual examination, most specimens exhibited catastrophic or irreparable failures. SEM analysis revealed that fracture origins consistently occurred on the loading surface, primarily within the major contact area of the loading ball. These fractures propagated coronoapically towards the inner part of the prostheses, where they were either stopped or redirected by the reinforcing fibers (Figure 5).

Discussion

This study investigated the potential impact of using various fiber types to reinforce direct inlay-retained FRC prostheses in hemisected molars, specifically regarding fatigue resistance and fracture patterns. Our first null hypothesis was rejected, as combining long and short FRCs (Groups 2A, 2B) significantly improved the fatigue resistance of the prostheses compared to the ones reinforced with only long fibers (Groups 1A, 1B) or short fibers (Groups 3A, 3B). Initially, unidirectional long fibers were utilized for endodontic posts,[47] extra- and intracoronal splints in periodontally compromised teeth,[48-50] and interim replacement of anterior teeth,[51,52] as they offer several advantages, such as improved esthetics, low wear on opposing dentition, the ability to bond the prosthesis to abutment teeth, lower cost, and potential for repairability.[53] Recent advancements in FRC materials have expanded their applications to the posterior region,[54] including long-term restorations of severely damaged single

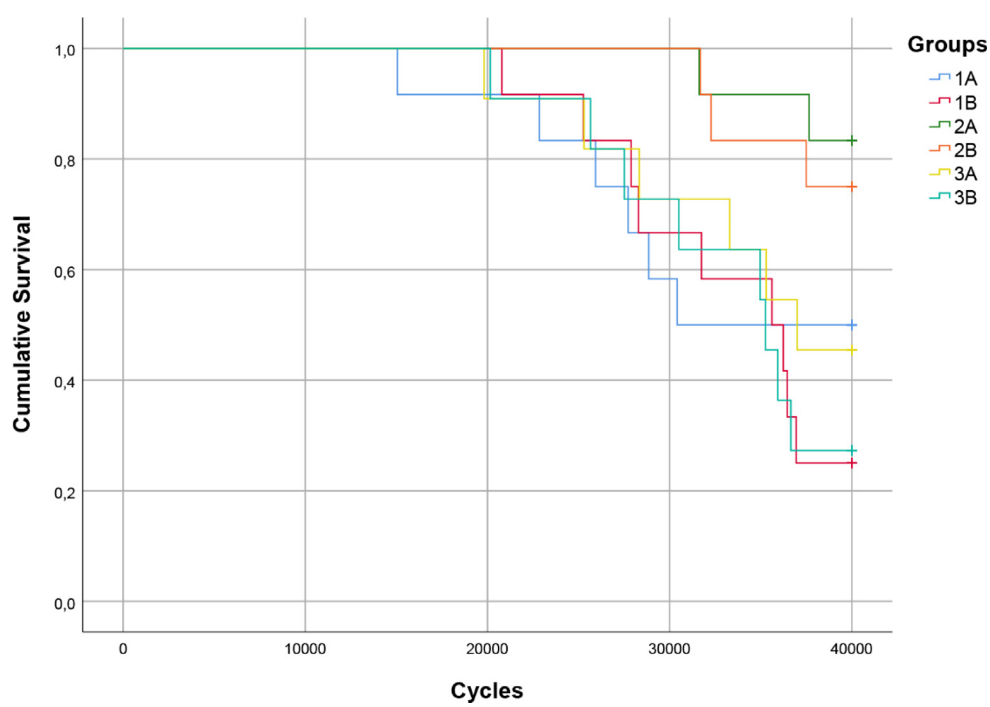

Figure 4 – Kaplan–Meier plots of the study groups.

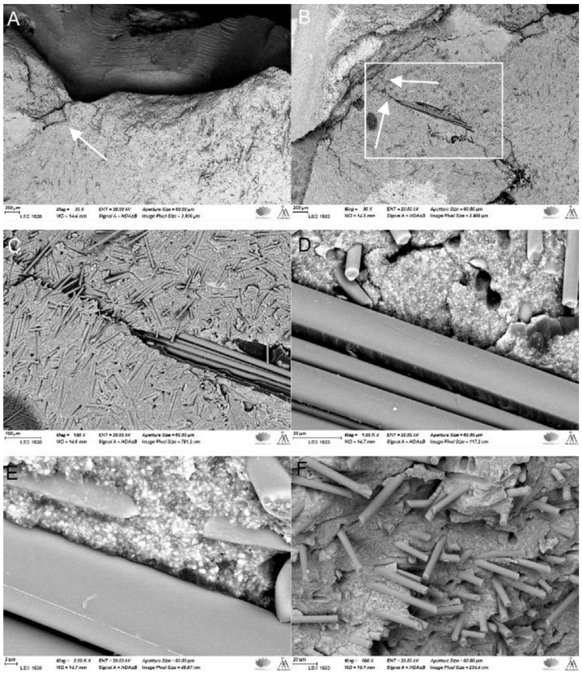

Figure 5 – SEM images at various magnifications (Group 2) illustrate crack propagation from the loading area apically into prostheses (arrows), where the cracks are halted upon encountering the long fiber bundles. The final image illustrates the pull-out of short fibers from the fracture surface.

teeth[55-57] and medium-/long-term short-span tooth replacements. These replacements can involve one or two pontics, cantilever or bilateral abutments, utilizing minimally invasive inlay-retained approaches that make use of existing cavities or micro-invasive surface-retained approaches.[58,59]

Traditionally, direct FRC fixed-partial prostheses consist of two types of composite materials: an FRC substructure or framework and a resin veneering composite, which is most commonly a conventional particulate-filled composite (PFC).[38,60] The limitations of conventional veneering composites – such as marginal discoloration, microleakage, recurrent caries, postoperative sensitivity, and fractures in large cavities – are partly due to their high volumetric shrinkage of 1-6%[61] and partly to their less-than-ideal mechanical properties, including flexural properties and fracture toughness.[62]

To address these issues, SFRC materials were developed. These materials incorporate short fibers that structurally resemble the fibrous composition of dentin and provide multidirectional reinforcement, replicating dentin's stress-absorbing characteristics.[63] SFRC materials have been successfully utilized for dentin replacement,[64] serving as a stress-absorbing layer in large MOD cavities[40,65] and in post-and-core restorations, both with and without long unidirectional fibers in endodontically treated teeth.[56,66-68] In several applications, SFRC has demonstrated superior fracture resistance and fracture toughness compared to conventional PFC materials.[69]

To date, only two studies have evaluated the use of SFRC alone for fabricating inlay-retained dental prostheses.[46,70] In our previous study, SFRC alone (Groups 3A, 3B) did not yield similarly promising results for inlay-retained dental prostheses. This outcome aligns with the findings of Cekic-Nagas et al, who assessed the load-bearing capacity of inlay-retained dental prostheses constructed solely from SFRC or from SFRC combined with a unidirectional FRC framework.[71] However, in their study, the packable version of SFRC was used, and the material was combined with PFC coverage, which creates significant differences in the study setup compared to our current research. Flowable SFRC was first utilized to fabricate an anterior prostheses for replacing missing anterior teeth. To date, this study, along with that of Lassila et al,[70] represents one of the few investigations testing flowable SFRC without PFC coverage for the fabrication of posterior inlay-retained FRC prostheses. Lassila et al, demonstrated comparable results between FRC prostheses made solely of flowable SFRC and PFC prostheses.[70] However, as PFC prostheses without any FRC substructure were not tested in our study, a direct comparison between the two studies is not possible.

In four of our study groups (Groups 1A, 1B, 2A, 2B), unidirectional long glass fibers were used as frameworks, where the fibers run parallel in a single direction. Due to their anisotropic nature, their resistance is greatest in the direction parallel to the fibers and weakest in the direction perpendicular to them.[28] To optimize fiber performance, the literature offers various recommendations concerning the ideal geometrical arrangement and number of long fiber bundles in the pontic.[60,72-74]

In the oral cavity, bending forces are most prominent in the frontal region, whereas shearing and torsional forces dominate in the lateral region.[74] Since long fiber bundles are highly resistant to tensile forces,[74] it is suggested that, in addition to the central horizontal bundle, additional vertical bundles can be placed at the pontic,[28,60] and lateral fiber bundles can be embedded within the approximal box-shaped cavity.

Alternatively, if the tooth surface remains intact, flat vestibular and/or oral fiber bundles can be positioned on the adjacent teeth,[75] or a hybrid anchorage involving inlay retention and wing retention may also be used.[76] However, the number and placement of fiber bundles are contingent on the available volume within the FRC prostheses. If incorporating lateral and vertical bundles proves challenging, using SFRC as a veneering composite in the pontic, instead of conventional PFC composite, may offer similar multidirectional reinforcement.

In our study, the combination of long and short fibers (Groups 2A-2B) significantly enhanced the fatigue resistance of inlay-retained FRC prostheses compared to prostheses reinforced solely with short fibers.[46] This finding aligns with the results of our previous pilot study.[46] Therefore, the authors recommend combining short and long fibers when fabricating such inlay-retained FRC prostheses in order to aid mechanical resistance and durability. The simultaneous presence of long and short fibers may provide several potential advantages. Short fibers are isotropic, offering reinforcement in all directions, whereas long unidirectional fibers are anisotropic, providing reinforcement in only one specific direction.[77-79] However, the reinforcement provided by long unidirectional fibers can be substantially higher (up to 100%) compared to that of short fibers (approximately 25%).[77-79]

In the literature, the combination of short and long fibers has also been successfully applied in large MOD restorations of endodontically treated teeth.[80] However, there are only a few studies that have examined its performance in inlay-retained FRC prostheses. The results of the present study align well with the findings of Cekic-Nagas et al, and Keulemans et al, which demonstrated that SFRC can enhance the fracture resistance of inlay-retained prostheses with a unidirectional FRC framework.[71,81] Nevertheless, both Cekic-Nagas et al, and Lassila et al, emphasized the superior performance of prefabricated CAD/CAM FRC prostheses compared to manually fabricated direct ones. This advantage is attributed to their more homogeneous structure, which reduces the risk of porosities and provides superior mechanical strength.[71]

In our study, the long fiber bundles were positioned horizontally in the occlusal third of the crown, functioning as an early stress-redirecting layer and creating a shorter working arm under loading.[82] Some authors have suggested placing the FRC framework as close as possible to the gingiva,[60] forming a U-shaped substructure that extends into the connectors, thereby aligning the fiber directions with those of the maximum principal stresses.[73] Given that, in the present study, the edentulous span was limited to only half a molar space, and considering that bending is directly proportional to the cube of the length and inversely proportional to the cube of the occlusogingival dimension of the pontic,[83] this difference may not have had a detrimental effect on the outcome.

Systematic reviews have reported the survival rate of fixed FRC prostheses to range from 73-94% after 5 years.[38,84] Failures primarily occur due to veneer-fiber delamination, debonding, and fractures, which tend to occur at the interface between the resin composite and fibers, as well as at loading points and connectors.[60,73] Failures occur mainly due to veneer-fiber delamination, debonding, and fractures that primarily occur at the interface between the resin composite and fibers, loading points, and connectors. In terms of fracture pattern, our second null hypothesis was accepted as mostly irrepairable fractures dominated among the fractured specimen.

Visual analysis indicated that crack propagation generally followed an oblique path from the occlusal surface to the gingival region through the connector. SEM images of the tested specimens revealed that cracks initiated at the loading surface (occlusal side of the connector) and advanced into the inner composite prosthesis. The cracks were then stopped or redirected by the embedded fibers. Notably, SFRC demonstrated close integration with the continuous fiber bundles, minimizing the potential for weak interfaces. The semi-interpenetrating polymer network (semi-IPN) structure of the polymer matrix in the continuous glass fiber bundles (everStick C&B) allowed for strong adhesion with the direct resin composite, ensuring reliable bonding. This interlocking or adhesive interaction likely explains the enhanced performance observed when combining both FRC systems.

Fiber pull-out was noticed in SFRC fracture surfaces, creating frictional desirable for toughness. These toughening mechanisms happen during the crack propagation and could explain why SFRC had higher toughness and strength than conventional PFC composite.

The occlusal anatomy may also contribute to delamination failures. Therefore, Özcan et al, recommended designing a shallow cusp morphology and ensuring that occlusal contact points are positioned on the mesial and distal sides of the pontic's occlusal surface to enhance the fracture resistance of inlay-retained FRC prostheses.[85] Consequently, in our study, the loads were applied to one of the connector regions of the pontics.

Interestingly, factorial ANOVA revealed that the restorative material significantly influenced the load-bearing capacity ($P < .05$), regardless of the periodontal support. In our previous study, we evaluated the effects of periodontal support levels and the presence or absence of root amputation on the fracture resistance of intracoronally splinted maxillary premolar-molar teeth.[86] The analysis showed a significant effect for root amputation, but neither the bone level nor the interaction between amputation and bone level was significant.

These results align with our present findings, where neither the periodontal status nor the interaction between material and periodontal status proved significant. It is worth noting that mechanical simulations and testing involving furcation involvement are scarce in the literature. Our findings contradict those of Szabó et al, who reported that furcation involvement significantly weakened root-amputated maxillary molars restored with either a direct filling or an overlay.[87] However, in their study, the teeth were not splinted in any way, which may explain the differences in the observed results. Due to the lack of studies dealing with the effect and proper simulation of compromised periodontal support, and also due to the in vitro nature of this study, our results regarding the effect of the level of periodontal support must be dealt with caution. Under clinical conditions, compromised support may influence the longevity of such prostheses through other modes (biologic failure, mobility, etc.), which is beyond the scope of our study setup.

Finally, the authors consider the novelty of this study to lie in the use of human teeth with standardized dimensions, the consistent preparation of restored units, the application of cyclic loading, and the simulation of varying levels of periodontal support.[88] Further investigations are warranted, as the existing literature lacks mechanical testing simulations replicating such severe yet frequently encountered periodontally compromised conditions.

The present study has certain limitations. Cyclic loading was not performed in a fluid chamber, which limits the comparability of the findings to *in vivo* conditions where saliva is continuously present during loading cycles. This aspect should be incorporated into future research designs. An additional, and arguably more critical, limitation is the absence of artificial aging and thermocycling. Previous studies have demonstrated that composite resin restorations may exhibit altered mechanical behavior following artificial aging compared to nonaged specimens.[89-91] Accordingly, future studies should also incorporate sample aging.

Conclusion

The integration of long and short FRC systems significantly improved the fatigue resistance of direct inlay-retained composite prostheses compared to using either short or long fibers alone. This combined approach also has the potential to mitigate the adverse effects associated with compromised periodontal support.

Author contribution

Conceptualization: B.Sz. and M.F.; *Methodology:* V.T.Sz., B.Sz. and M.F.; *Software:* G.B. and Zs.G.; *Validation:* G.B. and D.P.; *Formal analysis:* G.B., E.S. and L.L.; *Investigation:* V.T.Sz., Cs.M., B. Sz. and M.F.; *Resources:* S.G., L.L. and M.F.; *Data curation:* G.B. and Zs.G.; *Writing – original draft preparation:* V.T.Sz., M.F., E.S. and S.G.; *Writing – review and editing:* S.G.; *Visualization:* V.T. Sz., B.Sz. and D.P.; *Supervision:* S.G., E.S. and M.F.; *Project administration:* Cs.M.; *Funding acquisition:* M.F. All authors have read and agreed to the published version of the manuscript.

Ethics statement

All procedures in the study were approved by the Ethics Committee of the University of Szeged and the Medical Research Council of Hungary (BM/23566-1/2023), and the study was designed in accordance with the Declaration of Helsinki.

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Conflict of interest

Author ES works for Stick Tech – Member of the GC Group in R&D. All other authors declare to have no conflict of interest.

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