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Evaluation of fracture resistance and crack propensity of bulk-fill composite restorations reinforced by polyethylene fiber

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Abstract

Background In clinical restorative applications, different materials and techniques are used to replace lost tooth tissue and compensate for the fracture resistance that are essential for function. Further investigation is required to ascertain the effect of polyethylene fiber application, which is one of these interventions, on the fracture resistance, fracture location, reparability and crack propagation of premolar teeth restored with direct composite resin restorations. This in-vitro study aimed to evaluate fracture resistance and crack propagation of two bulk-fill composites (BRC) with/without polyethylene-fiber in extensive Class I resin composite restorations.

Methods Cavities were prepared on 40 mandibular premolars. In half of the samples ($n=20$), polyethylene-fiber (Ribbond Fiber/RF) coated with adhesive resin was placed on cavity floor. Half of the teeth were restored with SonicFill 3 and the other half with Charisma Bulk Flow ONE. The groups were as follows: SonicFill 3 + Fiber(SF + RF), SonicFill 3(SF), Charisma Bulk Flow ONE + Fiber(CO + RF), and Charisma Bulk Flow ONE(CO). Following 20,000 thermo-cycles fracture resistance (FR) was determined. Crack number/orientation were assessed with transillumination using two different wavelengths, before (t_0) and after preparation (t_p), and following fracture test (t_f). Visual examination was performed with micro-CT to evaluate the adaptation. Data were analyzed using Independent samples T-test, Fisher's Exact, Fisher Freeman Halton, Pearson Chi-Square and Cochran's Q Tests ($P<.05$).

Results No statistically significant difference was found between the FR of groups ($P=.994$) with and without RF ($P=.167$) according to BRC. The mean FR values in decreasing order were CO (761.09 ± 224.32) > SF + RF (671.08 ± 150.51) > CO + RF (669.95 ± 358.44) > SF (580.7 ± 269.04). A reduction in the formation of irreparable fracture patterns was detected in RF groups. Crack number/orientation did not differ according to BRC and RF application. Statistically significant increase was observed in crack formation over examination periods ($t_f > t_p > t_0$; $P<.001$).

Conclusions The reinforcement of large cavities with polyethylene fibers changed the fracture pattern of the restorations towards repairable, whereas had no effect on fracture resistance and crack formation. Furthermore, the placement of polyethylene fibers may have an adverse effect on the adaptation of the cavity. In clinical applications, both wavelengths can be used for transillumination testing in crack inspection.

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Keywords Crack propensity, Micro-CT, Polyethylene fiber, Sonic-activated bulk-fill, Transillumination

Introduction

The amount of remaining intact tooth tissue and structural factors such as interaxial dentin and marginal ridges, play a critical role in determining the prognosis for restoring teeth [1]. Loss of tooth tissue results in a significant weakening of tooth structure and fracture resistance, although the severity depends on the morphology of the cavity [2]. There has been an attempt to compensate for these decreasing fracture resistance values through various restorative materials and restoration techniques in clinical practices. In cavities with excessive loss of inter-axial dentin, direct restorative resin composites and polyethylene fiber applications have emerged as a valid option [2]. With its higher elasticity coefficient and flexural strength, polyethylene fiber could be considered to provide resistance to the restoration against elongation and deformations [2, 3].

In potential clinical circumstances such as premature occlusal contacts, thermal cycling, or long-term unilateral chewing, the formation of cracks is promoted when the force applied to the teeth exceeds the limit of the dentin-enamel elasticity [4]. During direct restoration stages with conventional composites, polymerization shrinkage creates stresses at the interface between the composite restoration and the tooth, as well as within the tooth structure and the resin composites [5]. These stresses can lead to crack formation, which is further exacerbated by chewing forces. Cracked teeth are also a common clinical problem, contributing to complicated clinical manifestations and uncertain prognosis [4]. Cracks are a prevalent cause of replacement of resin composite restorations, presenting with symptoms such as postoperative sensitivity, and a range of clinical consequences, including microleakage, discoloration, secondary caries, and pulpal complications [6, 7]. The early detection of cracks is significant for the protection of dental tissues. Commonly employed clinical methods for this purpose include magnification with an operating microscope, fiber-optic transillumination, and staining with dye [8, 9].

Despite having improved mechanical properties such as strength and stiffness, the low toughness of resin composites can be interpreted as a material's lack of energy absorption ability against rapid crack propagation [10, 11]. The network-like structure and multiple interwoven fibers of high molecular weight polyethylene can slow the propagation of cracks by better distributing the forces exerted on the restored tooth [12]. This approach may provide a less invasive and conservative option than some polymers and indirect restorative techniques. Furthermore, by directing fracture formation above the cementoenamel junction (CEJ), it can be aimed to prevent catastrophic failure and preserve the restorable tooth structure [13].

The increased clinical procedure stages in resin composite restorations combined with fibers might be technique sensitive and time-consuming [13]. This leads to the selection of a resin composite with low viscosity but high mechanical properties to improve the adaptation of the fiber to the restorative material and cavity base. The use of sonic-activated composites may be considered in this clinical protocol. Sonic Fill 3 does not compromise its mechanical properties as a result of its high filler ratio and it can be inserted into the cavity as it becomes more flowable due to its sonic activation property [14].

Although there are many studies examining the fracture strength of fiber-reinforced or conventional direct composite restorations reinforced with polyethylene fibers, to the best of the author's knowledge, only a few studies have examined fiber adaptation along with mechanical behavior [15–17]. Therefore, this study aimed to compare the fracture resistance of Sonic Fill 3 Bulk Fill and Charisma Bulk Flow One applied with polyethylene fibers. Furthermore, microcomputed tomography (micro-CT), which allows three-dimensional (3D) imaging of the entire tooth structure, was used to observe gap formation and Ribbond adaptation in different layers in Class I cavities. Despite the evidence presented in the extant studies that fiber has a significant impact on the stress dynamics at the enamel-composite interface, crucial factors that directly influence the success of the restoration, such as early detection of crack propensity, follow-up and their orientation have not been addressed sufficiently in the literature [18]. Crack tracking, which is assumed to be a factor in predicting the clinical performance of restorations, was included in the study. Transillumination technique for crack detection was applied with light at two wavelengths (green and red). The hypotheses (H_0) of this study were as follows:

1. Polyethylene fiber application has no effect on fracture resistance.
2. The restorative material used (bulk-fill resin composite versus sonic-activated bulk-fill composite) has no effect on fracture resistance.
3. Cavity preparation and loading through fracture test have no effect on enamel crack formation and orientation.
4. The use of different wavelengths in transillumination technique has no effect on crack detection.

Materials and methods

The study conformed to the tenets of the Declaration of Helsinki, and it was conducted with the approval of the Ethics Committee of …. University Faculty of Dentistry (reference number: 2023/137). The minimum sample size was calculated using G*Power (Version 3.1.9.6) based on ANOVA test with an effect size of 0.995, α = 0.05, and 1-β = 0.99, which suggested *n* = 8 per group. The effect size was determined by considering both pilot data and previously published literature [19]. In order to account for potential losses, the sample size was increased and 10 samples were prepared for each group.

Specimen preparation and restorative procedures

Forty freshly extracted, sound human mandibular premolars of similar size and dimensions were obtained from the Department of Oral and Maxillofacial Surgery, Faculty of Dentistry, Marmara University. After removal of debris and soft tissue remnants, the teeth were stored in physiological saline solution until use. Deviations in the size of the measurements of the teeth were kept within 10% of the mean. Exclusion criteria were teeth with caries, endodontic treatment or restoration. Furthermore, all extracted teeth were obtained with informed consent from participants aged between 18 and 25 years to minimize any differences in physical properties. The teeth were immersed in molten wax to obtain a wax layer 0.2–0.3 mm thick all over the root, starting 1 mm below the cementoenamel junction. The thickness of the wax layer was checked with calipers and excess wax layer was removed. The teeth were fixed in self-curing acrylic resin. The teeth and waxes were removed from the polymerized acrylic molds to obtain the standard thickness required for the impression material. To simulate periodontal ligament, light body elastomeric impression material (light-body polyvinyl siloxane) was applied over the root surfaces and the teeth were re-mounted in cured acrylic resin [20]. A standardized box-shaped cavity form was determined that would allow the placement of polyethylene fiber on the base. Class I cavities (2 mm x 2 mm x 4 mm) were prepared on the teeth using a round and shoulder diamond bur (ISO 001/018, Diamond burs, Chengdu Sani Medical Equipment Co.). A new bur was installed after each specimen. In the cavity preparation, the walls were prepared parallel to the long axis of the tooth and no bevel was formed at the cavity margins. While a thickness of 2 mm was confirmed by measuring the remaining tooth wall with a digital caliper, the dimensions of the cavity were measured using periodontal probe (Hu-Friedy, Rotterdam, Netherlands). Cavity depth was measured as 4 mm from the central fossa to the pulpal floor of the cavity.

Enamel surfaces of cavities were etched with 37% phosphoric acid for 30 s (for selective etching), rinsed with water spray, and gently air dried. Cavities were classified randomly into 4 groups ($n = 10$). The groups were as follows; The groups were as follows; Group 1: Ribbond Fiber + Optibond Universal/SonicFill 3, Group 2: Optibond Universal/SonicFill 3, Group 3: Ribbond Fiber + Gluma Bond Universal/Charisma Bulk Flow One, and Group 4: Gluma Bond Universal/Charisma Bulk Flow One (Fig. 1). The adhesive system of the same manufacturer was utilized in each composite group, in accordance with the manufacturer's instructions. Optibond Universal or Gluma Bond Universal was applied to the cavities and polymerized for 20 s (Valo Cordless, Ultradent; 1000 mW/cm^2). In the preparation of Ribbond fiber, the material was cut and soaked in adhesives for 2 min before used. The excess adhesive resin was then removed with a hand instrument. In half of the samples, polyethylene Ribbond fiber (2 mm x 2 mm x 0.35 mm; Ribbond Inc., Seattle, WA, USA) coated with adhesive resin (OptiBond Universal or Gluma Bond Universal) was placed on the pulpal cavity floor and walls and cured with an LED light-curing unit for 20 s. The cavities were restored in a monolayer with SonicFill 3 (Kerr) and flowable Charisma Bulk Flow ONE (Kulzer) bulk-fill composites up to the central fossa according to manufacturers' instructions. Valo Cordless (Ultradent) LED-curing unit with a power output of 1000 mW/cm^2 was utilized for polymerization for 20 s. Uniform anatomical restorations were made without modeling the pits and fissures. Finishing and polishing were completed with the Sof-Lex discs (24 and 8 µm grains; 3 M ESPE). Cavity preparations and restorative procedures were performed by the same operator (A.M.).

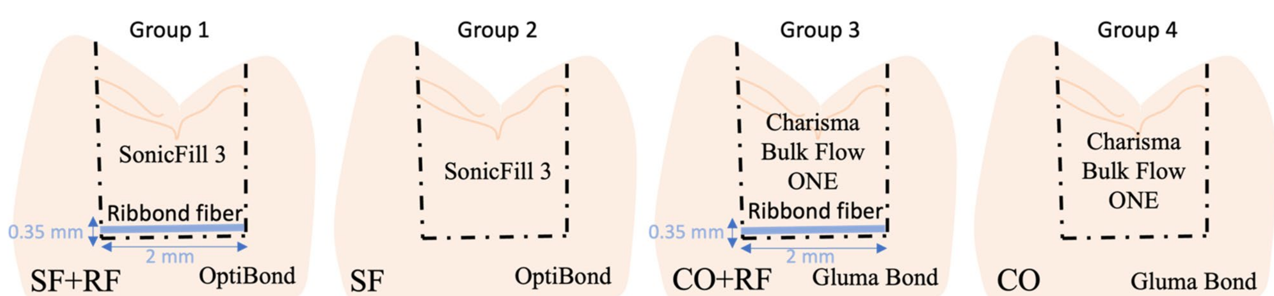

Fig. 1 Representation of sample groups obtained according to restorative materials and polyethylene fiber application in buccolingual section

Table 1 The brand name, manufacturer information, and contents of the materials used in the study

Brand Name	Manufacturer	Content
Sonicfill 3 Lot Number: 9,137,888	Kerr, USA	Barium glass, silicon dioxide, Bis-GMA Bis-EMA, TEGDMA, EBPDMA, MPS Filler w/V% = 83.5/65.9
Charisma Bulk Flow One Lot Number: M010022	Kulzer, Germany	Bis-GMA, UDMA, TEGDMA, EBPDMA, Ba-Al-B-F-Si glass, SiO_2, YbF_3 Filler w/V% = 65/41
Ribbond Fiber Lot Number: D758T0	Ribbond, USA	Ultra-high stress polyethylene, homopolymer $H\text{-}(CH_2\text{-}CH_2)_n\text{-}H$
Optibond Universal Lot Number:9,027,574	Kerr, USA	Bis-GMA, HEMA, GPDM, Photo-initiators, fillers, ethanol
Gluma Bond Universal Lot Number: M0100S1	Kulzer, Germany	10-MDP phosphate monomer, 4-META, dimethacrylate resins, acetone, fillers, initiators, silane

Abbreviations:Bis-GMA = bisphenol-A glycidyl methacrylate; *Bis-EMA* = Bisphenol A ethoxylate dimethacrylate; *TEGDMA* = triethylene glycol dimethacrylate; *EBPDMA* = ethoxylated bisphenol-A-dimethacrylate; *MPS* = 3- (trimethoxysilyl) propyl methacrylate; *UDMA* = urethane dimethacrylate; *SiO_2* = silicon oxide (silica); *YbF_3* = ytterbium fluoride; *Ba-Al-B-F-Si glass* = Barium aluminum boro fluorine silicate glass; *10-MDP* = 10-methacryloyloxydecyl dihydrogen phosphate; *HEMA* = hydroxyethylmethacrylate; *4-META* = 4-methacryloxyethyl

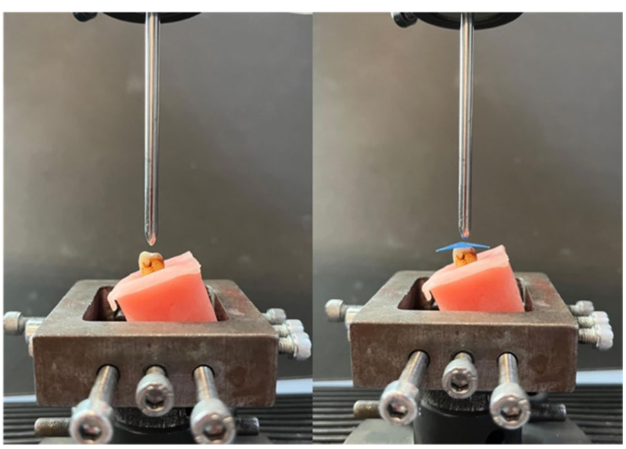

Fig. 2 Positioning and axial loading of the restoration

Restored teeth were stored in distilled water at 37 °C for 24 h. The brand name, manufacturer information, and contents of the materials used in the study are presented in Table 1.

Thermo-cycle protocol
For the aging procedure, samples were subjected to 20,000 thermo-cycles to simulate 2 years of clinical service (5–55 °C distilled water with a 20 s dwell time and transfer time of 10 s) using a Thermocycler (SD Mechatronik).

Fracture resistance (N) test
Fracture resistance values were measured using a universal testing device (Shimadzu AG-X, Shimadzu Corp) at a crosshead speed of 0.5 mm/min until failure occurred. A compressive load was applied in the direction of the longitudinal axis of the center of the fossa with a help of a stainless-steel cylindrical shaped curved tip measuring 3 mm in diameter (Fig. 2). The fracture forces for each tooth have been calculated in Newton (N).

Fracture location, pattern and failure type analysis with stereomicroscope
Fracture location (proximal, buccal, and lingual), fracture pattern (according to reparable failures above the CEJ or irreparable failures below the CEJ) [21, 22] and failure type (adhesive failure if there was complete detachment at the interface of the 2 structures; cohesive failure if it occurred inside the material structure; and mixed failure combination of adhesive and cohesive failure) [23] were evaluated by visual inspection using stereomicroscope (Leica MZ7.5, Leica Microsystems) under x10 and x40 following fracture test. Specimens that fractured without separation were noted.

Enamel crack detection and tracking
Crack number and orientation analysis with fiber-optic transillumination technique
Crack number and orientation (vertical, horizontal, and oblique) were assessed using two different wavelengths (TransLume™ Lenses, Valo Cordless, Ultradent) (Fig. 3). The position of the LED during the evaluation was made reproducible using an anatomical reference point to prevent standardization losses and reduced variability in the observations that may be encountered in transillumination examination.

During the study, each surface of each tooth was photographed with a DSLR camera (Canon 1300D) and macro lens (100 mm) under standard conditions at three time points for 'enamel crack tracking': before cavity preparation (t_0), after cavity preparation (t_p), and following the fracture test (t_f). The images were transferred to a computer software program (ImageJ, National Institutes of Health) and the crack location was defined as shown in Fig. 3, by two calibrated operators (B.D.K. and A.M.) In the pilot study, 50 images were scored by observers, and the results were then compared to those obtained by a senior trainer. In a process that was conducted blindly, an 80% agreement was reached among the observers [24]. Care was taken to detect differences between pre-existing cracks and cracks created by cavity preparation, and fracture test. For this purpose, the teeth are examined by dividing them into 6 regions, as shown in Fig. 3.

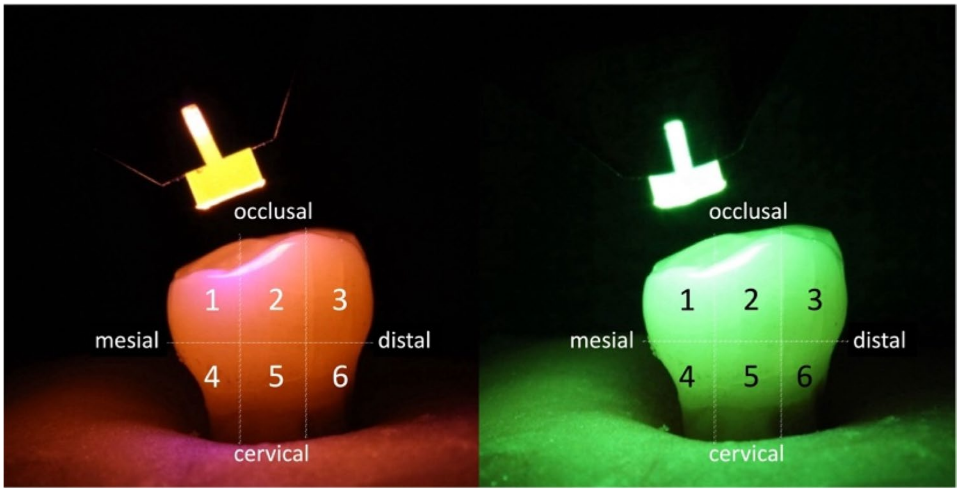

Fig. 3 Detection of cracks using two different wavelength transillumination

Micro-CT analysis

The specimens were mounted on a jig to ensure stability in the instrument for imaging. Three samples from each group were scanned using a micro-CT device (SkyScan 1275) following aging with thermo-cycle. The acquisition parameters were set as follows: 80 kilovoltage peak (kVp), 125 milli-amperes (mA), frame average 3, and rotation step 0.5° at 13 µm/pixel size. The two-dimensional coronal and sagittal images obtained were analyzed on axially prepared sections using Dataviewer (version 1.5.6.2 Skyscan) software and images were processed using the rotation feature of the program. 3D reconstruction of restorations was performed using N Recon software (program version 1.6.1.3, Bruker Skyscan).

Marginal continuity and adaptation between the dental tissues and the restorative materials and the gaps within the bulk-fill composites were visually examined. Qualitative insight into marginal adaptation was provided in the limited sample size.

Statistical analysis

Fracture resistance values were analyzed with IBM SPSS V23 using the independent samples T-test. For the analyses, compliance with the normal distribution was examined with Shapiro-Wilk and skewness/kurtosis coefficients. Analysis results are presented as mean and standard deviation. The number and orientation of crack line values were analyzed using Fisher's Exact, Fisher Freeman Halton, Pearson Chi-Square, and Cochran's Q Tests. Fracture pattern, fracture location, and failure type data were summarized by number and percentage. Pairwise comparisons were analyzed by chi-square test. The significance level was set at $P<.05$.

Table 2 Comparison of fracture resistance values

Ribbond	SonicFill 3	Charisma Bulk Flow ONE	Test Statistics [1]	*p*	Cohen's d (%95 CI)
Not Applied	580.7 ± 269.04	761.09 ± 224.32	−1.457	0.167	0.728 (0.013–1.444)
Applied	671.08 ± 150.51	669.95 ± 358.44	0.008	0.994	−0.004 (−0.697–0.689)
Test Statistics [1]	−0.829	0.610			
p	0.421	0.552			
Cohen's d (%95 CI)	0.415 (−0.286–1.115)	−0.305 (−1.002–0.392)			

[1]Independent samples t-test; mean ± standard deviation

Results

RF application did not result in a statistically significant difference in the mean maximum force (N) values of the Charisma Bulk Flow ONE ($P=.552$) and Sonic Fill 3 ($P=.421$) restorations. (Table 2) The maximum force for each group is listed from lowest to highest in the following order SF (580.7), CO + RF (669.95), SF + RF (671.08), and CO (761.09). (Table 2) When the groups with and without Ribbond were compared according to the restorative material, no statistically significant difference was detected. ($P=.994$, $P=.167$) (Table 2).

A reduction in the formation of irreparable fracture patterns after the fracture test was observed in the Ribbond applied groups (SF + RF: 10%, CO + RF: 10%) compared to the SF (40%) and CO (30%) groups (Figs. 4 and 5).

The distribution of lingual fractures was lower in the RF groups (SF: 90%, SF + RF: 50%, CO: 50%, CO + RF: 40%) (Fig. 4).

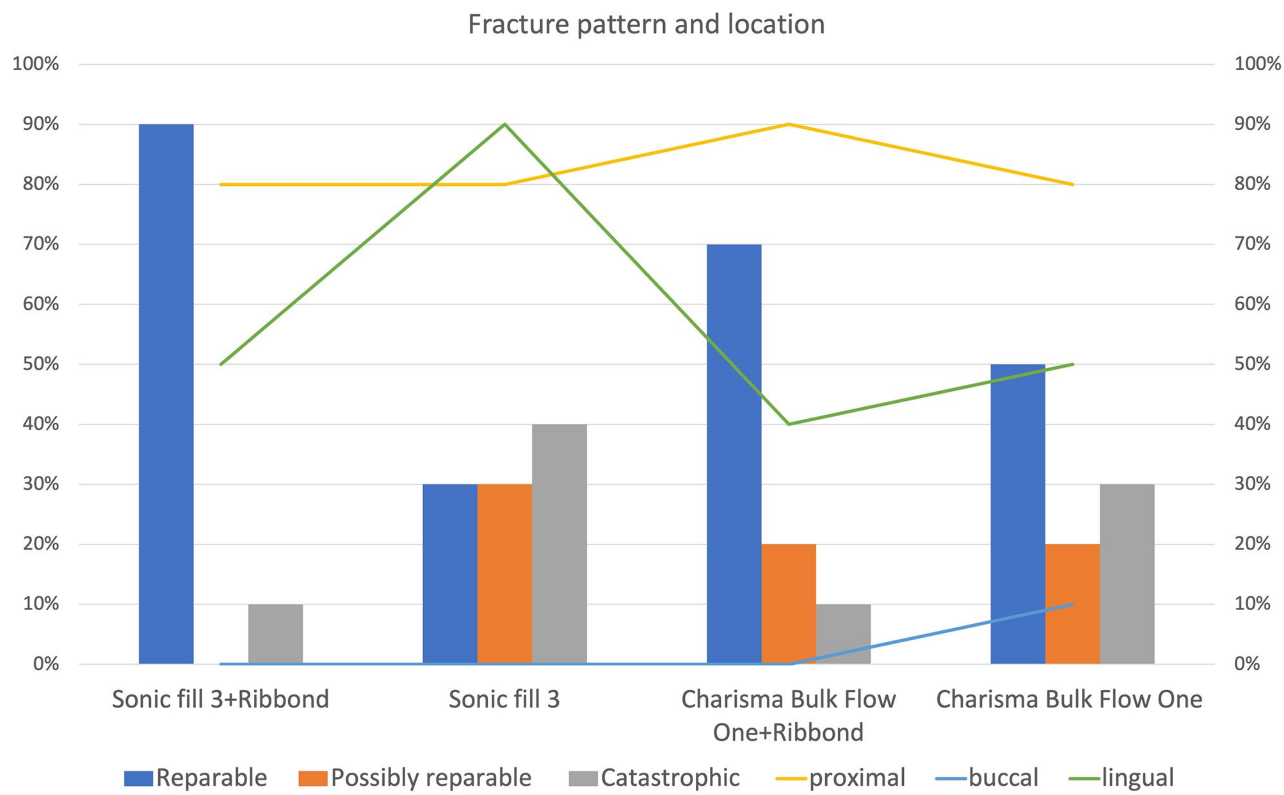

Fig. 4 Distribution of fracture patterns and locations for each group

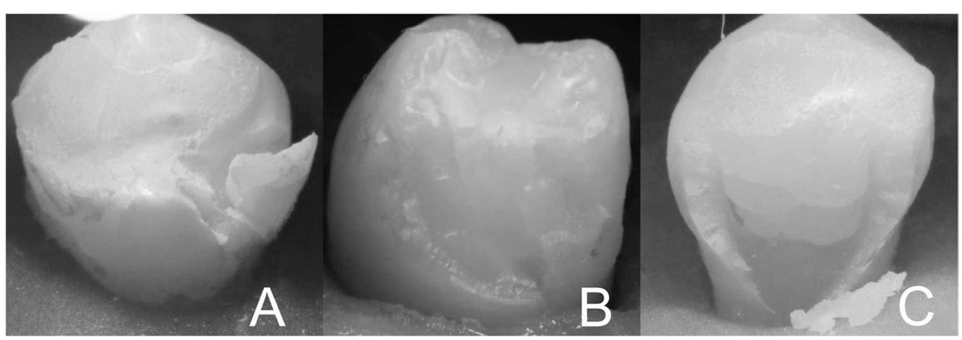

Fig. 5 An example is shown for each fracture pattern: **a** reparable (fracture above CEJ), **b** possibly reparable (fracture 1 mm or less apical to CEJ), **c** catastrophic (fractures more than 1 mm apical to CEJ)

The adhesive failure rate was higher in the RF groups (SF: 30%, SF + RF: 50%, CO: 40%, CO + RF: 50%) according to the distribution of failure types (Fig. 6).

The teeth were examined under red and green light transillumination before and after preparation, and after the fracture test. It was noted that the cracks increased after preparation and fracture test (Fig. 7).

Significant differences were observed in comparisons over time for horizontal, oblique, and vertical crack types (P=.018, P<.001, and P<.001, respectively). However, crack number and orientation did not differ according to restorative material and RF application (P>.05).

An increase was observed after preparation and after fracture test in all groups for all crack types. (Table 3)

Using different lights in crack examination did not reveal a significant difference according to propensity and orientation. (Table 4) (P>.05).

When the adaptations of the Ribbond groups were examined at the cavity floor by micro-CT, discontinuous margins were observed in comparison to the non-Ribbond groups (Fig. 8. A-D). However, intra-material porosity was present in both the Ribbond and non-Ribbond groups for Sonicfill 3 and Charisma Bulk One (Fig. 8. A, D).

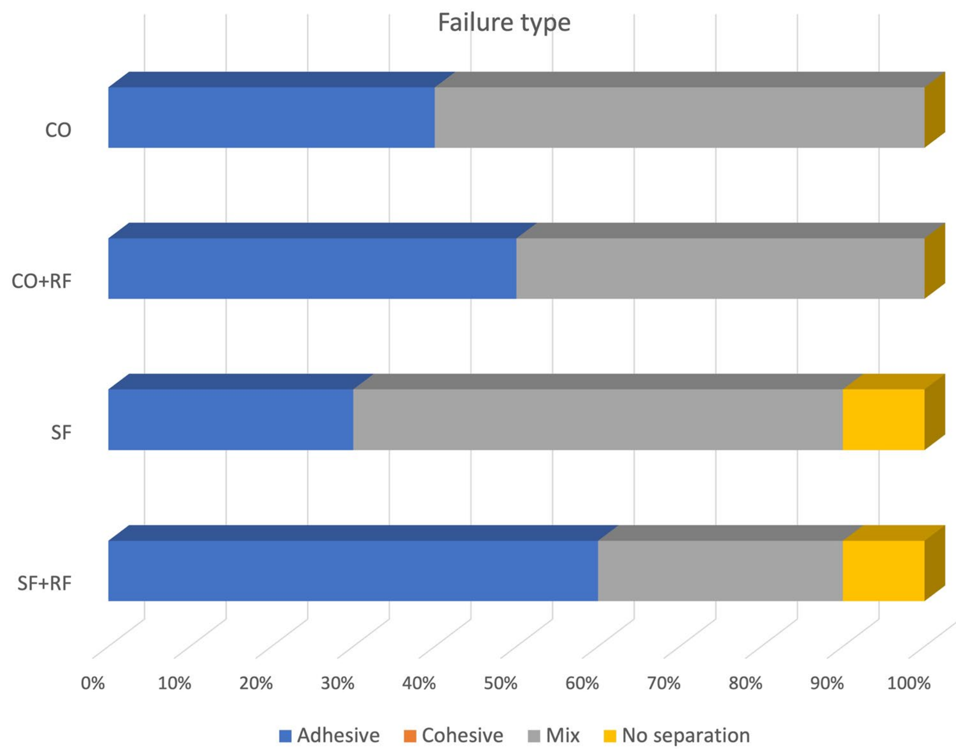

Fig. 6 Distribution of failure types for each group

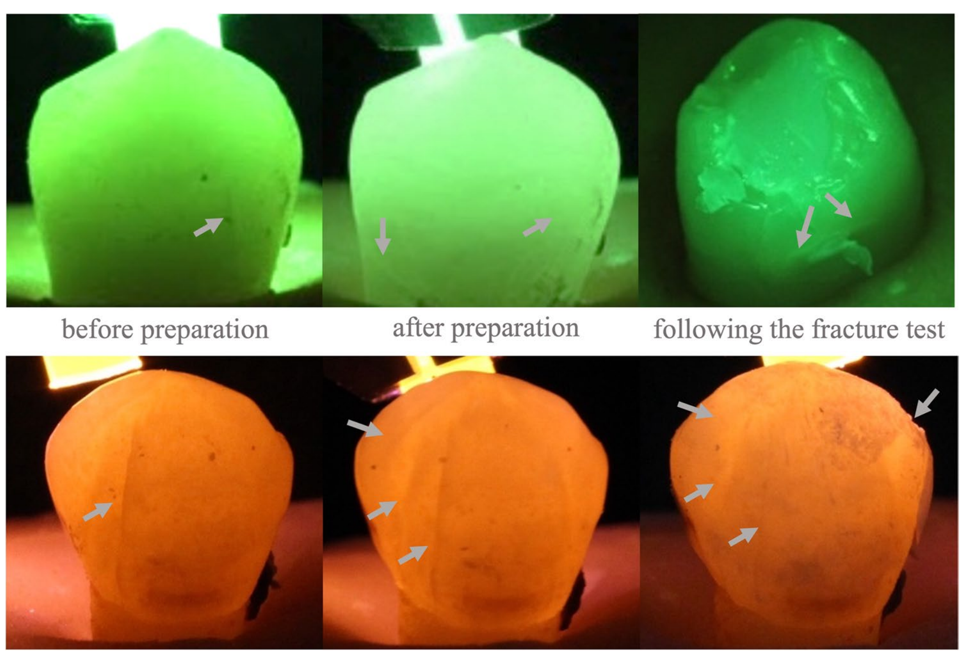

Fig. 7 Cracks diagnosed using transillumination technique with red and green light, at initial, after preparation and after fracture test of restorations are marked with arrows

Discussion

Fracture tests provide insight into the biomechanical analysis of materials and the strength of bonding interfaces between materials [25]. Moreover, the loads required in the fracture test may demonstrate the ability of the polyethylene fiber placed at the base of the cavity to match to the toughness of dentin and its stress-bearing potential [26, 27]. In this in vitro study, Class I cavities that involve the removal of interaxial dentin were designed to reduce tooth strength in premolars, which

Table 3 Comparison of crack propensity and distribution of orientation at examination periods to the material used and RF application

Crack propensity	**SF**		**SF + RF**		**CO**		**CO + RF**		**Total**		**Test statistics**	***p***
	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)		
Initial	9 (45)	11 (55)	11 (55)	9 (45)	13 (65)	7 (35)	8 (40)	12 (60)	41 (51.2)	39 (48.8)[a]	2.952	0.399*
After preparation	4 (20)	16 (80)	3 (15)	17 (85)	6 (30)	14 (70)	3 (15)	17 (85)	16 (20)	64 (80)[b]	1.793	0.720**
After test	4 (20)	16 (80)	3 (15)	17 (85)	5 (25)	15 (75)	2 (10)	18 (90)	14 (17.5)	66 (82.5)[b]	1.750	0.755**
Test statistics									33.95			
p									< 0.001***			
Crack orientation	SF		SF + RF		CO		CO + RF		Total		Test statistics	p
Vertical	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)		
Initial	13 (65)	7 (35)	15 (75)	5 (25)	18 (90)	2 (10)	12 (60)	8 (40)	58 (72.5)	22 (27.5)[a]	5.266	0.153*
After preparation	10 (50)	10 (50)	8 (40)	12 (60)	12 (60)	8 (40)	8 (40)	12 (60)	38 (47.5)	42 (52.5)[b]	2.206	0.531*
After test	12 (60)	8 (40)	7 (35)	13 (65)	10 (50)	10 (50)	4 (20)	16 (80)	33 (41.3)	47 (58.8)[b]	7.582	0.055*
Test statistics									25.61			
p									< 0.001***			
Horizontal	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)		
Initial	18 (90)	2 (10)	18 (90)	2 (10)	20 (100)	0 (0)	20 (100)	0 (0)	76 (95)	4 (5)[a]	3.586	0.317**
After preparation	18 (90)	2 (10)	18 (90)	2 (10)	20 (100)	0 (0)	18 (90)	2 (10)	74 (92.5)	6 (7.5)[ab]	2.450	0.591**
After test	15 (75)	5 (25)	18 (90)	2 (10)	20 (100)	0 (0)	17 (85)	3 (15)	70 (87.5)	10 (12.5)[b]	5.914	0.125**
Test statistics									8.00			
p									0.018***			
Oblique	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)		
Initial	17 (85)	3 (15)	16 (80)	4 (20)	18 (90)	2 (10)	14 (70)	6 (30)	65 (81.3)	15 (18.8)[a]	2.720	0.487**
After preparation	14 (70)	6 (30)	13 (65)	7 (35)	12 (60)	8 (40)	10 (50)	10 (50)	49 (61.3)	31 (38.8)[b]	1.843	0.606*
After test	8 (40)	12 (60)	12 (60)	8 (40)	10 (50)	10 (50)	12 (60)	8 (40)	42 (52.5)	38 (47.5)[b]	2.206	0.531*
Test statistics									20.341			
p									< 0.001***			

*Pearson Chi-Square Test; **Fisher Freeman Halton Test; ***Cochran's Q Test; a-b; There is no difference between times with the same letter

Table 4 Comparison of crack propensity and directions according to light type of transillumination technique

	Crack propensity	Green light	Red light	Total	Test statistics	*p*
Initial	(-)	18 (45)	23 (57.5)	41 (51.2)	0.801	0.371*
	(+)	22 (55)	17 (42.5)	39 (48.8)		
After preparation	(-)	9 (22.5)	7 (17.5)	16 (20)	0.078	0.780*
	(+)	31 (77.5)	33 (82.5)	64 (80)		
After test	(-)	7 (17.5)	7 (17.5)	14 (17.5)	0.000	1.000*
	(+)	33 (82.5)	33 (82.5)	66 (82.5)		
Vertical						
Initial	(-)	28 (70)	30 (75)	58 (72.5)	0.063	0.802*
	(+)	12 (30)	10 (25)	22 (27.5)		
After preparation	(-)	18 (45)	20 (50)	38 (47.5)	0.05	0.823*
	(+)	22 (55)	20 (50)	42 (52.5)		
After test	(-)	16 (40)	17 (42.5)	33 (41.3)	0.000	1.000*
	(+)	24 (60)	23 (57.5)	47 (58.8)		
Horizontal						
Initial	(-)	37 (92.5)	39 (97.5)	76 (95)	---	0.615**
	(+)	3 (7.5)	1 (2.5)	4 (5)		
After preparation	(-)	36 (90)	38 (95)	74 (92.5)	---	0.675**
	(+)	4 (10)	2 (5)	6 (7.5)		
After test	(-)	34 (85)	36 (90)	70 (87.5)	0.114	0.735*
	(+)	6 (15)	4 (10)	10 (12.5)		
Oblique						
Initial	(-)	32 (80)	33 (82.5)	65 (81.3)	0.000	1.000*
	(+)	8 (20)	7 (17.5)	15 (18.8)		
After preparation	(-)	27 (67.5)	22 (55)	49 (61.3)	0.843	0.359*
	(+)	13 (32.5)	18 (45)	31 (38.8)		
After test	(-)	23 (57.5)	19 (47.5)	42 (52.5)	0.451	0.502*
	(+)	17 (42.5)	21 (52.5)	38 (47.5)		

*Yates Correction; **Fisher's Exact Test

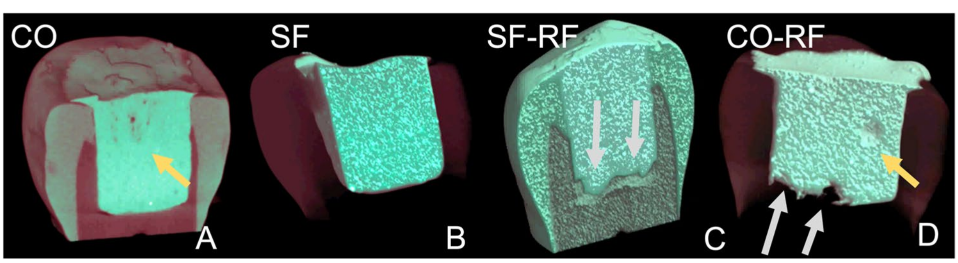

Fig. 8 Micro-CT examination of adaptation to cavity floor in groups with and without Ribbond application (A-D), Gaps and discontinuous margins (indicated by grey arrows, C, D), intra-material porosity in the Ribbond and non-Ribbond groups for Sonicfill 3 and Charizma Bulk One (indicated by yellow arrows A, D)

are subjected to more destructive lateral forces than molars [28]. Class I cavities were prepared to the highest cavity configuration, which refers to the ratio of bonded surfaces to free surfaces [29]. In the current study, the effects of two different restoration protocols, with and without polyethylene fiber application under two different bulk-fill materials, on the fracture resistance, crack tendency and crack orientation were investigated. A summary of the hypothesis testing outcomes, including acceptance/rejection status and key findings, is provided in Supplementary Table S1. Restorations combining RF and bulk-fill composites were found to result in similar fracture resistance and crack propensity. Additionally, the two restorative materials exhibited similar performances regardless of RF use. Therefore, the first and second null hypotheses were accepted in terms of fracture resistance values. Although no statistically significant differences were found between the groups, examination reveals noticeable numerical variation among the mean fracture resistance values (e.g., Cohen's d values ranged from moderate to large across comparisons). These differences, may suggest underlying influences such as variation in material composition (e.g., filler content and resin matrix structure), and specimen-specific differences in anatomy and mineralization.

Although there was no statistically significant difference between the groups, RF application resulted in higher fracture resistance values for Sonic Fill 3 (Cohen's d = 0.415), whereas, surprisingly, a decrease was observed for the Charisma Bulk Flow ONE group (Cohen's d = − 0.305). Although the results of the studies predominantly indicate that fiber application increases fracture resistance [30], a few studies have concluded that it does not lead to an improvement [15, 31–33]. Zotti et al. stated that complete removal of the interaxial dentin in teeth without endodontic treatment and with a preserved pulp chamber resulted in a loss in fracture strength of the tooth. This situation has been associated with the loss of the ability to distribute residual loading forces when RF is placed beyond a certain depth [3]. The results of the present study suggest that Ribbond Fiber requires sufficient interaxial residual dentin to support the remaining tooth structure. AlJarboua et al. attributed the similar unexpected result which were obtained from the test group without endodontic treatment to the Ribbond-to-composite ratio, which may adversely affect the adaptation of the Ribbond and the integrity of the restoration [19]. The divergence in outcomes can be explained by the different cavity preparation designs, remaining wall thickness, orientation of the fiber, and differences in the location of fiber insertion in the studies [2, 15]. Numerous studies investigating fracture resistance in teeth with or without root canal treatment have included restorations of MOD and Class II cavities [13, 19, 30, 33–35]. To the author's knowledge, only one of the studies evaluating the use of Ribbond in Class I cavities examined fracture resistance [36], whereas the other two studies investigated microleakage [37] and bond strength [38]. The relatively minimal effect of fiber application on fracture strength may be attributable to the greater preservation of sound tissue in prepared Class I restorations in comparison with MOD restorations.

As with restorative materials, the quality, chemical composition and application technique of the preferred adhesive systems are also factors affecting the fracture strength [39]. The surface wetting required to optimize bonding is achieved by the combined action of functional monomers and solvents found in the adhesive system [40]. In the present study, the adhesive system of the same manufacturer was utilized in each composite group for the purpose of impregnation of polyethylene fiber, as well as for the bonding of dentin and enamel tissues to the restorative material. Gluma Universal, a blend of 4-META and acetone, exhibits noteworthy wetting capability and abrasive efficiency. On the other hand, Optibond Universal, characterized by its GPDM-based formulation and a significantly higher acetone content compared to ethanol, exhibit optimum wettability [41]. The review, which incorporates numerous studies, concludes that GPDM is the functional monomer that results in statistically higher bonds in dentin/enamel when compared to 10-MDP-based materials [42]. Although no statistically significant difference was found between the fracture strength values of the groups with two different restorative materials and adhesives, with and without fiber application, further studies are needed to specifically evaluate the effect of the adhesive used to impregnate the fiber on fracture strength.

In the present study, the highest rate of catastrophic fractures below the CEJ was in the SF group, although reparable fractures outnumbered irreparable fractures in all groups. The application of RF changed the distribution of fracture patterns in the groups towards repairable. The results of the current study are in line with the studies conducted by Agrawal et al. [13], Soto-Cadena et al. [23], and Sáry et al. [43], where the incorporation of polyethylene fibers has shown the reparable patterns of fracture. Therefore, it is conceivable that the use of RF could improve the fracture pattern in fracture performance or as an adjunct to dentine replacement. Another finding of the current study, the reduction in lingual cusp fracture rates as a result of RF application, also supports this view. However, in the static test method employed, it should be considered that the force is applied longitudinally to the axis of the center of the fossa.

The mean maximal bite-force magnitude ranges between 424 and 583 N at the premolar area [44]. Chewing forces increased up to 800 N in patients with parafunctional habits [45]. According to the results obtained from the current study, the restorations show acceptable performance against normal chewing forces.

In resin composite restorations incorporating RF, the fiber-resin bond should maintain the integrity of the restoration by withstanding the forces while providing an energy absorption mechanism suitable for crack arrest. At this stage, the impregnation of the fiber with resin and its integration into the polymer matrix are an important and technically sensitive step for strength [17]. In the current study, the effect of the applied fiber on integrity with the composite and the cavity floor was examined using micro-CT. Micro-CT examinations revealed marginal adaptation deficiencies and discontinuous marginal integrity when fiber was used for all composite and adhesive groups. There are limited investigations evaluating composite restorations and polyethylene fiber insertion in terms of gap formation [15, 17]. Although no statistical difference was observed in the fracture resistance between the groups, the increased gap formation with fiber application is consistent with the similar study of Deger et al. [15] During the polymerization of resin-based composites, the shrinkage vector may be more noticeable along the occluso-gingival axis than along the bucco-lingual axis [46]. It has been stated that polyethylene fiber prevents shrinkage along the length of the fibers and thus preserves the horizontal dimensions [47]. In various studies, the deterioration of the margins after aging in the fiber groups has been attributed to the vertical shrinkage of the resin composites as a result of thermal fluctuations, despite the presence of horizontally oriented fibers that minimize horizontal shrinkage to a minimum [22, 48]. Alternatively, another explanation for the results may be that the insertion of the polyethylene fiber into the cavity is a technically sensitive application; when the manual impregnation of the fibers is not performed adequately, the adhesion between the fibers and the composite resin matrix or the cavity may be reduced [2, 30]. Porosity created in the material or an excess of residual monomer within the matrix may affect the interface of the fiber or the restorative material, altering its properties and leading to failure [17]. Moreover, Hasija et al. also evaluated the marginal adaptation of polyethylene fiber-reinforced Class II composite restorations in teeth with affected dentin with scanning electron microscopy. The results showed that the use of polyethylene fibers did not improve marginal adaptation in affected dentin [49]. However, the results of the studies by Sfeikos et al. and Sadr et al. suggested the opposite [17, 37]. Sfeikos et al. concluded that the use of fibers with the wallpapering technique in Class I composite restorations can reduce marginal microleakage. Sadr et al. stated that the formation of gaps at the cavity floor of the bulk-fill composite can be reduced by fiber insertion. These contradictory results can be attributed to the differences in the restorative materials and methodologies used.

As the resin composite polymerizes, it contracts and shrinks. Also, this shrinkage can place stress on the bonded interfaces or lead to the formation of cracks that can affect the durability and lifespan of the restoration [24, 50]. Loading forces affect different areas of the tooth, leading to crack propagation and fracture risk; therefore, it is clinically important to evaluate crack propagation [51]. Another factor that distinguishes the present study from the others is that enamel crack tracking was carried out before and after loading the fiber applied specimens to observe the relationship of cracks with fracture behavior and whether they propagate under loaded conditions.

When initially comparing the number of cracks, right after the cavity preparation procedure and following fracture test, a significant increase was observed in all groups. In the study by Silva et al., in which cracks were evaluated by transillumination, it was found that the cracks that were present prior to the restorative procedures showed a slight increase after the restoration was placed and subjected to fatigue loading. This increase was due to shrinkage stress in the composite after restoration, rather than fatigue testing [52]. Also, in the current study, the orientation of cracks was examined. High stress concentration and reduced enamel thickness in the cervical area may increase the tendency for horizontal crack formation near the cavity floor [24]. The third null hypothesis was partially rejected, there was no difference in enamel crack orientation between groups according to testing time points.

Canobra et al. analyzed the effect of fiber application on the fracture pattern and crack propagation in the material and showed that the use of polyethylene fibers arrested the cracks initiated at the occlusal and had a reinforcing effect on the restorative material. However, the stress was concentrated on the tooth-restoration interface, which was observed to contribute to the failure of interface. These findings are in accordance with the increased adhesive failure mode observed in the RF groups as reported in the present study [53].

Studies have demonstrated that transillumination is a reliable technique for tracking enamel crack propagation [24, 54, 55]. In the present study, transillumination was performed using two different wavelengths of light—red (625–660 nm) and green (540–570 nm)—which were selected based on their differing optical interactions with dental hard tissues. Green light, with its shorter wavelength and higher scattering coefficient, may enhance the visualization of surface-level enamel irregularities and shallow cracks, whereas red light, due to its deeper penetration capacity and lower scattering, can aid in the detection of deeper or subsurface fractures. The use of these specific wavelengths is supported by previous studies demonstrating their diagnostic utility in crack detection and structural assessment of composite restorations [9, 56]. In our results, both wavelengths exhibited similar performance in detecting cracks in terms of their presence and orientation, thereby supporting the acceptance of the fourth null hypothesis. However, the inability of transillumination—regardless of wavelength—to determine the depth of cracks remains a methodological limitation. Despite this constraint, the current study offers a valuable baseline for selecting restorative materials and evaluating the influence of polyethylene fiber application on crack development and propagation. Although dyes and optical coherence tomography (OCT) are well-documented diagnostic modalities for enamel crack detection, they present certain limitations in in vitro and clinical use. Dye-based methods may overestimate crack presence due to superficial staining, while OCT, although offering high-resolution imaging, is not yet widely available in routine clinical practice [8]. In this context, the red and green transillumination technique may provide a non-destructive, real-time, and cost-effective alternative. However, further validation studies are warranted to determine the sensitivity and specificity of this technique relative to gold standard methods.

Although this study attempted to select teeth of comparable size, it is not possible to standardize the exact size and configuration as well as their mineral content. The micro-CT findings were evaluated qualitatively and not subjected to statistical testing. Although the limited number of scanned specimens per group ($n = 3$) restricts the generalizability of the conclusions regarding marginal adaptation, the validity of the visual observations remains intact. Future studies involving larger sample sizes are needed to validate these observations and assess statistical correlations. It is also notable that the implementation of polyethylene fiber applications necessitates a high degree of technical precision in the clinical setting. While a large effect size in the current study ensures high statistical power, it may also carry the risk of overestimating the true power of the study; therefore, this limitation was acknowledged in the interpretation of the findings.

Focusing on the main effect of fiber and restorative material in this study, the fiber was placed in a horizontal orientation at the floor of the cavity. Further studies can be performed to investigate the technical sensitivity and fracture strength in different fiber orientations. This study did not encompass evaluations of polymerization shrinkage or bond strength which are related to fracture resistance. The specimens were not exposed to conditions that would simulate intraoral conditions (e.g. artificial saliva, simulated chewing). As this study is an in vitro study, some biases and limitations are inherent [57], and the data should be interpreted with this in consideration. The current study's high standard deviation values of the fracture resistance are common in mechanical tests on anatomically irregular specimens-in this case the occlusal surface of premolars. One of the key limitations of this in-vitro study is the absence of dynamic loading protocols to simulate masticatory function. While static loading offers valuable insight into maximum fracture resistance, it does not reproduce the repetitive, multidirectional stresses of actual occlusal function. This limits the direct interpretation of the findings with regard to clinical performance, particularly with regard to long-term fatigue behaviour. Further studies should include fracture tests with dynamic loading or the assessment of the effect of laterotrusive occlusal forces by applying angled loads. While the findings offer useful insights into the mechanical behaviour of fiber-reinforced composites, their application to clinical practice remains tentative and should be validated through in vivo studies.

Conclusions

In light of the obtained results, the following conclusions can be drawn;

1. Using RF in large Class I cavities produced favourable results in terms of fracture patterns and tubercle preservation.
2. Since higher fracture resistance values are obtained, it may be preferable to apply SF combining with fiber.
3. Both wavelengths tested in fiber-optic transillumination appeared suitable for crack inspection under in-vitro conditions.
4. Adaptation deficiencies were observed in cavity floors where RF and bulk-fill composites were combined, which warrants cautious interpretation and further clinical investigation.

Abbreviations

10-MDP	10-Methacryloyloxydecyl dihydrogen phosphate
4-META	4-Methacryloxyethyl trimellitate anhydride
Ba-Al-B-F-Si glass	Barium–aluminum–boro–fluorine–silicate glass
Bis-EMA	Bisphenol-A ethoxylate dimethacrylate
Bis-GMA	Bisphenol-A glycidyl methacrylate
BRC	Bulk-fill resin composite
CEJ	Cementoenamel junction
CO	Charisma Bulk Flow ONE
EBPDMA	Ethoxylated bisphenol-A dimethacrylate
FR	Fracture resistance
GPDM	Glycerophosphate dimethacrylate
HEMA	2-Hydroxyethyl methacrylate
LED	Light-emitting diode
MPS	3-(Trimethoxysilyl) propyl methacrylate
OCT	Optical coherence tomography
RF	Ribbond Fiber
SD	Standard deviation
SF	SonicFill 3
SiO_2	Silicon dioxide
TEGDMA	Triethylene glycol dimethacrylate
UDMA	Urethane dimethacrylate
YbF_3	Ytterbium fluoride
μCT/Micro-CT	Micro-computed tomography

Supplementary Information

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Supplementary Material 1

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Authors' contributions

Conceptualization, A.A.Ş., A.M., B.D.K., P.Y.A., E.K., B.T., and C.T.;methodology, P.Y.A., E.K., and B.T.;software, A.A.Ş., A.M., B.D.K.;formal analysis, A.A.Ş., A.M., B.D.K., P.Y.A., E.K., and B.T.;investigation, A.M., and B.D.K.;data curation, A.M., and B.D.K.;writing—original draft preparation, A.A.Ş., A.M., B.D.K.;writing—review and editing, A.A.Ş., A.M., B.D.K., P.Y.A., E.K., and B.T.; supervision, P.Y.A., E.K., B.T., and C.T.;funding acquisition, P.Y.A., E.K., B.T., and C.T.;administration, A.A.Ş., A.M., B.D.K.All authors have read and agreed to the published version of the manuscript.

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Data availability
The data that support the findings of this study are available on request from the corresponding author. Corresponding Author: Ayşe Aslı Şenol, Email: asli.tuncer@marmara.edu.tr.

Declarations

Ethics approval and consent to participate
The study protocol was approved by the Ethics Committee of the Marmara University Faculty of Dentistry (protocol number: 2023/137), and it is certified that the study was conducted in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Informed consent was obtained from each patient for using extracted teeth.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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