Adhesive Properties of Bonded Orthodontic Retainers to Enamel: Stainless Steel Wire vs Fiber-reinforced Composites

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Purpose: The objectives of this study were to compare the bond strength of a stainless steel orthodontic wire vs various fiber-reinforced composites (FRC) used as orthodontic retainers on enamel, analyze the failure types after debonding, and investigate the influence of different application procedures of stainless steel wires on bond strength.

Materials and Methods: Caries-free, intact human mandibular incisors (N = 80, n = 10 per group) were selected and randomly distributed into 8 groups. After etching with 37% H_3PO_4 for 30 s, rinsing and drying, bonding agent (Stick Resin) was applied and light polymerized. Then one of the following FRC materials was applied on the flowable composite (Stick Flow) using standard molds: group 1: Angelus Fibrex Ribbon; group 2: DentaPreg Splint; group 3: everStick Ortho; group 4: Ribbond. In group 5, Quad Cat Wire was applied in the same manner as in FRC groups. In group 6, after applying bonding agent (Stick Resin), Quad Cat Wire was placed directly on the tooth surface and covered with Stick Flow composite. In group 7, after bonding agent (Heliobond) was applied, Quad Cat Wire was placed directly on the tooth surface and covered with Tetric Flow composite. In group 8, after applying bonding agent (Heliobond) and polymerization, Tetric Flow composite was applied, not polymerized, and Quad Cat Wire was placed and covered with Tetric Flow again. Specimens were thermocycled for 6000 cycles between 5°C and 55°C and loaded in a universal testing machine under shear stress (crosshead speed: 1 mm/min) until debonding occurred. The failure sites were examined under an optical light microscope. Data were analyzed using one-way ANOVA and the Tukey-Kramer adjustment test (α = 0.05).

Results: Significant differences were found between the groups (p = 0.0011) (ANOVA). Bond strength results did not significantly differ either between the FRC groups (groups 1 to 4) (6.1 ± 2.5 to 8.4 ± 3.7 MPa) ($p > 0.05$) or the wire groups (groups 5 to 8) (10.6 ± 3.8 to 14 ± 6.7 MPa) ($p > 0.05$). Failure types varied within the FRC groups, but mainly composite was found left adhered on the enamel surface at varying degrees. In the stainless steel wire groups, when the retainer was applied onto the bonding agent and then covered with flowable resin, partially attached composite on the enamel was often found after debonding. When the wires were embedded in the flowable composite, the Heliobond group (group 8) showed more adhesive failures between the enamel and the composite compared to group 5, where the bonding agent was Stick Resin.

Conclusion: Regardless of their application mode, stainless steel orthodontic bonded retainers delivered higher bond strengths than those of fiber retainers. The differences were statistically significant compared to those of Angelus Fibrex Ribbon and DentaPreg Splint.

Keywords: bond strength, fiber-reinforced composite, lingual retainer, orthodontics, relapse, stainless steel wire.

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During orthodontic treatment, the position of teeth is adjusted in order to correct malocclusion. There is an inherent tendency for teeth to relapse to their original, pretreatment position after the removal of orthodontic appliances.[1,11] With the possibility of acid etching and bonding, it has become common practice to apply bonded fixed retainers for long-term retention of the achieved orthodontic results.[2,7] Currently, such retainers are often made of either stainless steel wires or fiber-reinforced composites (FRC) of diverse types. Limited clinical studies have shown that there is a relatively high failure rate ranging between 2.9% to 47% in a comparatively short follow-up pe-

Fig 1 Mandibular incisor embedded in autopolymerized polymethyl methacrylate with the labial surface exposed for bonding purposes.

riod.[1-3,7,15] The failure type is usually either detachment of the wire retainer from the tooth surface or at the wire and/or resin composite interface. Although the reasons for these failures have not been extensively studied, several factors are described in the dental literature, such as insufficient composite material and/or abrasion of the composite,[3,4] less abrasion resistance and wear as a consequence of chewing or tooth brushing,[3,4] thickness of the wire,[15] and intermittent forces of mastication.[3,4] Another reason for debonding rates was attributed to the forces resulting from tension in the wire or between the wire and the teeth when the wire has not been adapted properly to the surface of the teeth.[3] Nevertheless, detachment of the bonded retainers has negative consequences for the treatment result, since the teeth may change position or relapse to their original position after the completion of the orthodontic treatment. This is costly for both the medical system and the patient, as it renders the lengthy and costly previous treatment ineffective, possibly making retreatment necessary.

Recently, FRC materials have been introduced for the fabrication of fixed dental prostheses (FDP), root posts, periodontal splints, and also as possible alternatives to stainless steel wire retainers for both active and passive applications in orthodontics. Resin pre-impregnated FRCs have a suitable flexural modulus and flexural strength for functioning successfully in the mouth as restorative materials.[16,31] It is thought that elimination of the metal wire in the retainer by using FRC systems may lead to more stable bonding, since adhesion of such retainers would solely rely on adhesion of the flowable composite or the resin matrix of the FRC to the etched and bonded enamel.

Theoretically, FRC materials are attractive because of their elastic modulus, esthetics, pliability, and the possibility of chemical adhesion both to the composite materials and the tooth, as opposed to the metal wires. Considering the clinical failures with stainless steel retainers related to debonding, especially the adhesion aspect warrants the comparison of FRC materials to their metallic counterparts. FRC materials are available in different forms and volumes, either preimpregnated with different resin monomer matrices or requiring impregnation prior to application by the clinician. The adhesive performance of the FRCs may vary depending on the variations in their inherent properties and impregnation. Although individual studies exist on adhesion of resin based materials to enamel, to the authors' knowledge, no research has been conducted to date comparing the adhesive properties of FRC splint materials with conventionally bonded stainless steel wires in the same study design. Both FRC and stainless steel wires are bonded to enamel in orthodontic wire applications using resin based materials, but their flexural behavior may vary due to the variations in the adhesion of resin materials to resins and metals. Furthermore, different application modes of stainless steel wires have been noted in the orthodontic literature, ie, placing the wire directly on the etched and bonded enamel[3,4] or embedding the wire in flowable resin composite or bonding agents with various properties/compositions[3,4,35] that may affect the bond strength and the failure types.

Because resin-based materials adhere better to enamel than do metals,[21] it was hypothesized that FRC materials would demonstrate higher bond strength than the metal ones, and that the bond strength of the stainless steel wires would increase when the wires were embedded in flowable composite, instead of being applied directly onto the bonding agent on the enamel.

Preimpregnated systems usually involve monomers like urethane dimethacrylate (UDMA), urethane tetramethacrylate (UTMA), bisphenol glycidylmethacrylate (bis-GMA), or polymethyl methacrylate (PMMA).[9,19] Evidence is still lacking on whether ultrahigh molecular weight polyethylene (UHMWPE) fibers can be used to fabricate durable FRC restorations.[10,27,31] Criticism has been focused on the inadequate interfacial adhesion between polyethylene fibers and dental polymers[30] compared to glass and silica fibers, which can be silanized.[13,30] Therefore, it was also hypothesized that silanized and pre-impregnated glass-fiber FRCs would possess better adhesive properties than plasma-coated, custom impregnated polyethylene FRC materials.

Therefore, the objectives of this study were twofold: 1. to compare the bond strength and failure types of a commonly used stainless steel orthodontic wire with differently impregnated FRC materials with various textures, and 2. to investigate the influence of different application procedures of stainless steel wires.

Table 1 Brand names, group numbers, compositions, manufacturers and batch numbers of the materials used in this study

Brand name	Groups	Composition	Manufacturer	Batch number
Angelus Interlig	1	E-glass/bis-GMA	Angelus; Londrina, Brazil	2199
DentaPreg Splint	2	S2-glass, mixture of dimethacrylates, initiators and stabilizers	ADM; Brno, Czech Republic	4742
everStick Ortho	3	E-glass/PMMA/bis-GMA	StickTech; Turku,	000088
Ribbond	4	Ultra High Molecular Weight Polyethylene	Ribbond; Seattle, WA, USA	9543
Quad Cat Wire	5-8	Stainless steel, three-strand twisted wire 0.022" x 0.016"	Quad Cat, GAC International; New York, NY, USA	0197
StickResin		Silanated silica 30% - 70% 2,2- bis[4-(2-hydroxy-3-methacryloxyro-poxyl)]-phenonylpropane 30% - 70% triethyleneglycol dimethacrylate	StickTech	5504765
Heliobond		Monomer matrix: dimethacrylate < 60% bis-GMA < 40% triethyleneglycol	Ivoclar Vivadent; Schaan, Liechtenstein	H29583 154518
StickFlow		Mixture of resin based on bis-GMA, methacrylates, catalysts, stabilizers, pigments	StickTech; Turku, Finland	D3-DA3-3
Tetric Flow		< 14% bis-GMA < 8% triethylene glycoldimethacrylate < 15% urethanedimethacrylate	Ivoclar Vivadent	J01476 154518

MATERIALS AND METHODS

Specimen Preparation

Eighty caries-free human mandibular central incisors of similar size, stored in distilled water with 0.1% (wt/vol) thymol at room temperature, were selected from a pool of recently extracted teeth. To determine that the enamel was free of crack lines, all teeth were evaluated under blue light transillumination. The roots were then sectioned with a diamond bur under water cooling. The crowns were mounted in polyethylene rings (diameter: 15 mm, thickness: 10 mm), with the buccal surface exposed, using autopolymerized polymethyl methacrylate (Candulor; Wangen, Switzerland) (Fig 1). Before embedding, the teeth were cleaned of any remaining soft tissue and calculus and stored in distilled water with 0.1% (wt/vol) thymol up to 2 months until the experiments. The enamel surfaces were cleaned and polished using water and fluoride-free pumice (Zircate Prophy Paste, Dentsply Caulk; Milford, DE, USA, batch #077809) with a prophylaxis brush (Hawe Prophy-Cup Latch-Type, KerrHawe; Bioggio, Switzerland, batch #960/30), rinsed with water, and dried using an air syringe.

Bonding Procedures

In all groups, labial enamel surfaces were etched with a 37% orthophosphoric acid (TopDent, DAB Dental; Upplands Väsby, Sweden) for 30 s and then rinsed thoroughly using an oil-free air-water spray for 20 s. The enamel surfaces were air dried until they appeared frosty. Description of brands, compositions, manufacturers, and batch numbers of FRC and wire retainers are listed in Table 1. Representative SEM (JSM-5500, JEOL Instruments; Tokyo, Japan) micrographs of the FRC materials and stainless steel wire are presented in Fig 2.

FRC Retainers (Groups 1 to 5)

All FRC retainers were bonded following the same procedures with the same adhesive resin and the flowable resin material. The FRCs were cut by means of a pair of special scissors (Ribbond fiber cutter, Ribbond; Seattle, WA, USA) to the same length (3 mm). A filler- and solvent-free light-curing bonding agent (Stick Resin, StickTech; Turku, Finland) was applied with a microbrush on the acid-etched enamel surface and blown into a thin layer. It was then light polymerized for 40 s with a conventional halogen light curing unit (Demetron LC, SDS Kerr; Danbury, CT, USA) (light output: 400 mW/cm^2). The irradiation distance between the exit window and the resin surface was maintained at 2 mm to obtain adequate polymerization. Flowable resin composite (Stick Flow, StickTech) was applied to the enamel surface and the respective FRC material was placed on the bed of the flowable composite, arranged horizontally on the largest area of the incisor in a rectangular polyethylene mold (3.2 x 2.2 x 1.5 mm) (Fig 3). The FRC materials were rewetted with the bonding agent (Stick Resin) and then covered with the flowable resin (StickFlow,

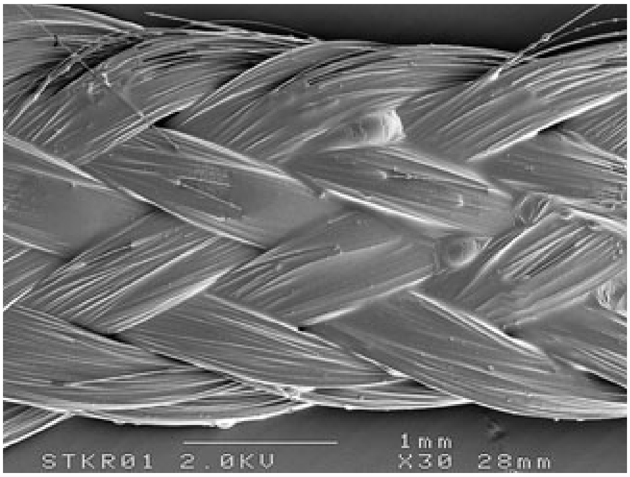

Fig 2a Representative SEM image of Angelus Fibrex Ribbon (original magnification 80X).

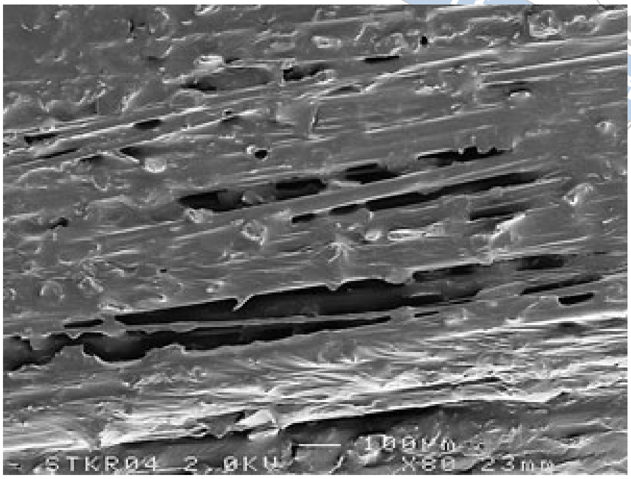

Fig 2b Representative SEM image of DentaPreg Splint (original magnification 80X).

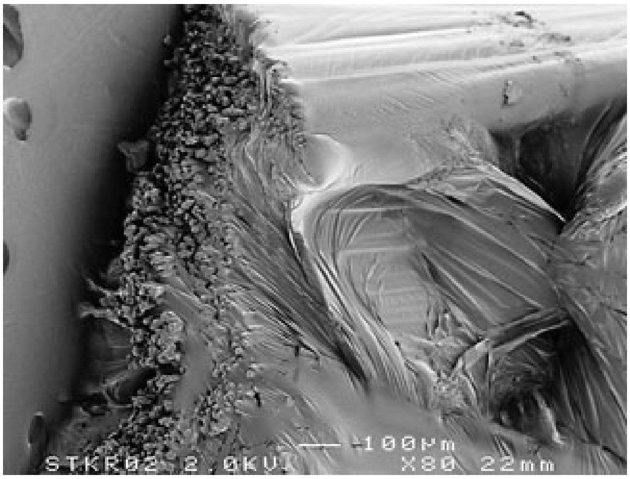

Fig 2c everStick Ortho (original magnification 80X). Note the resin impregnation of the fibers on as-received samples.

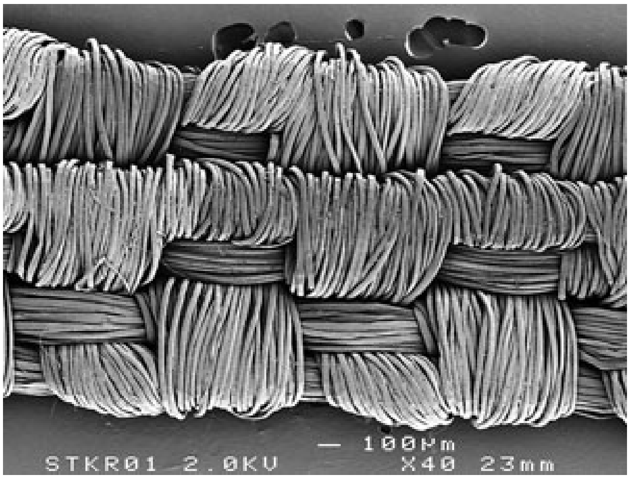

Fig 2d Ribbond (original magnification 40X).

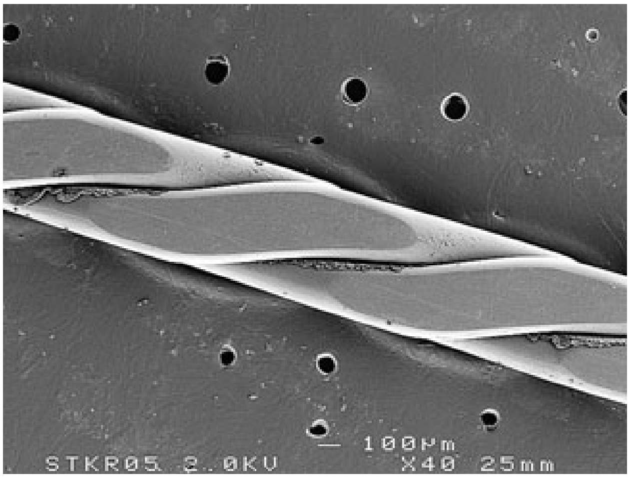

Fig 2e Quad Cat stainless-steel wire (original magnification 40X).

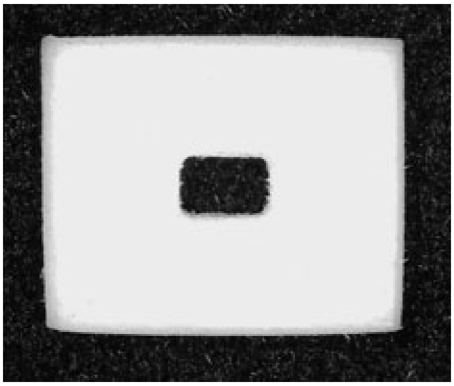

Fig 3 Rectangular polyethylene mold (3.2 x 2.2 x 1.5 mm) used for positioning the retainer and the flowable resin in a controlled manner.

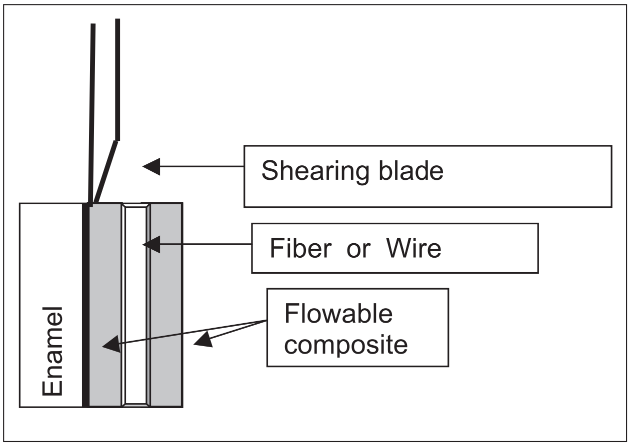

Fig 4a Schematic drawing of the cross-section of a specimen showing FRC or wire in relation to their application modes and the position of the shearing blade of the universal testing machine.

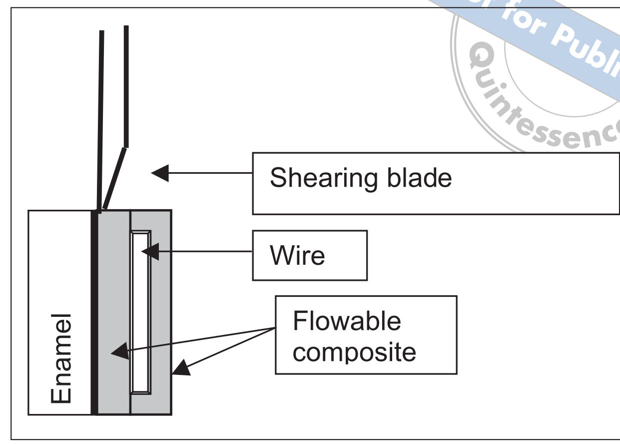

Fig 4b Schematic drawing of the cross-section of a specimen in Group 6 showing wire in relation to their application modes and the position of the shearing blade of the universal testing machine.

StickTech). This was also light polymerized for 40 s from a distance of 2 mm.

Stainless Steel Wires (Groups 5 to 8)

The orthodontic retainer wire used in this study was a flexible, braided, rectangular, stainless-steel wire (Quad Cat, 0.022 in x 0.016 in, GAC International; Bohemia, NY, USA).

Specimens in group 5 were prepared in the same manner with the procedure used for the FRC materials. In groups 6 to 8, the attempt was made to simulate different aspects of commonly used clinical methods. In groups 7 and 8, a different bonding agent and a flowable composite was used.

Group 6: A filler and solvent-free light-curing bonding agent (Stick Resin, StickTech) was applied with a microbrush on the acid-etched enamel surface and blown into a thin layer. It was then light polymerized for 40 s with a conventional halogen light curing unit (Demetron LC, SDS Kerr) (light output: 400 mw/cm^2). The irradiation distance between the exit window and the resin surface was maintained at 2 mm to obtain adequate polymerization. A piece of wire (3 mm) which was previously bent to adapt to the individual surface of each specimen, was placed on the tooth surface, and flowable composite (Stick Flow) was applied on top of the wire. This was then light polymerized for 40 s.

Group 7: The same protocol was followed as described for group 6 but a different bonding agent (Heliobond, Ivoclar Vivadent; Schaan, Liechtenstein) and flowable resin (Tetric Flow, Cavifill 210 A3, Ivoclar Vivadent) were used.

Group 8: The same materials were used as in group 7, but this time after bonding agent application, flowable composite was applied and the wire was placed in the bed of this flowable resin. The wire was then covered again with flowable composite, and light polymerization was performed.

The specimens were stored in distilled water with 0.1% (wt/vol) thymol solution at 37°C for one week and thermocycled 6000 times between 5ºC and 55°C (dwell time: 30 s, transfer time from one bath to the other: 2 s) (Willytec; Gräfelfing, Germany).

Shear Bond Testing

The specimens were mounted in the jig of the universal testing machine (Zwick ROELL Z2.5 MA 18-1-3/7; Ulm, Germany) where the force was applied at the composite/retainer-enamel interface from the occluso-cervical direction. The shearing blade had a taper of 45 degrees at the tip. The specimens were loaded at a crosshead speed of 1.0 mm/min until failure occurred, and the stress-strain curve was analyzed with the proprietary software program (Zwick ROELL). The force required to shear-peel the retainer was recorded and converted into MPa using the known surface area of the mold (7.04 mm^2) representing the bonded area. Schematic drawings of the FRC and wires in relation to their application modes and the shear blade are depicted in Fig 4. Subsequently, digital photographs (Nikon D1, Micro Nikon 60 lens; Tokyo, Japan) were taken of the substrate surfaces and the debonded retainers.

Failure Analysis

After debonding, the failure sites were examined by two calibrated operators (E.K., M.Ö.) both visually and using an optical microscope at different magnifications (up to 40X). A scoring system was created for failure type evaluation considering adhesive or cohesive failures at two interfaces, namely, enamel base/flowable resin, base or covering flowable resin/FRC/wire retainer, as well as cohesive failures within FRC or wire retainer (Table 3).

Statistical Analysis

Statistical analysis was performed using Statistix 8.0 for

Table 2 The mean shear bond strength (MPa) values for the experimental groups

Groups	Mean (+SD)	Homogeneous groups		
1	6.9±2.2		B	C
2	6.1±2.5			C
3	7.6±2.6	A	B	C
4	8.4±3.7	A	B	C
5	11.7±2.5	A	B	C
6	10.6±3.8	A	B	C
7	13±6.6	A	B	
8	14±6.7	A		

*The same letters indicate no significant differences (Tukey's test, α = 0.05). For group description see Table 1.

Windows (Analytical Software, Version 8.0, 2003; Tallahase, FL, USA). The means of each group were analyzed with one-way ANOVA. Because of the significant group factor ($p = 0.0011$), multiple comparisons were made with the Tukey-Kramer adjustment test to determine the significant differences between groups, where the dependant variable was shear bond strength and the independent variable was various combinations of application procedures and materials. P values less than 0.05 were considered to be statistically significant in all tests.

RESULTS

Shear Bond Strength

The results of the shear bond strength test for the FRC and stainless steel wire are presented in Table 2 and Fig 5. One-way ANOVA showed a significant difference between the groups ($p = 0.0011$).

Bond strength results did not significantly differ either between the FRC groups (groups 1 to 4) (6.1 ± 2.5 to 8.4 ± 3.7 MPa) ($p > 0.05$) or the stainless steel wire groups (groups 5 to 8) (10.6 ± 3.8 to 14 ± 6.7 MPa) ($p > 0.05$) (Tukey's test). Of the stainless steel wire groups, group 8 (14 ± 6.7 MPa) showed significantly higher results than those of two FRC materials, namely group 1 (Angelus Fibrex Ribbon) (6.9 ± 2.2 MPa) and group 2 (DentaPreg Splint) (6.1 ± 2.5 MPa) ($p < 0.05$).

Both E-glass or S2-glass FRC retainers (groups 1 to 3) did not show significant differences compared to UHMWP FRC (group 4) ($p > 0.05$).

Failure Types

Table 3 presents the modes of failures for the FRC and stainless steel retainers after debonding.

Enamel fractures were slightly more frequent (5 out of 40) in the FRC retainer groups than in the wire groups (2 out of 40). In none of the FRC retainer groups were adhesive failures between the enamel and the composite observed.

Failure types varied within the FRC retainer groups. The most frequently observed failure types were 1a (5/40) and 1b (17/40), where flowable composite remained adhered to the enamel surface at varying degrees after debonding. This failure type was followed by the cohesive failures within the FRCs, regardless of their preimpregnation and texture (16/40).

In the stainless steel wire groups, when the retainer was applied on the bonding agent and then covered by flowable resin (groups 6 and 7), partially attached composite was often found on the enamel after debonding. When the retainers were embedded in the flowable composite, the Heliobond + Tetric Flow group (group 8) showed more adhesive failures between the enamel and the composite compared to group 5, where the bonding agent was Stick Resin and the flowable composite was Stick Flow.

DISCUSSION

Although much research is currently being conducted in diverse fields of FRC applications in dentistry, very few studies have focused on the use of FRCs as orthodontic retainers.[6,11,25] High failure rates of bonded orthodontic post-treatment stabilization splints have been reported,[1-4] and therefore FRCs were considered as possible alternative materials for such applications. Since debonding remains a clinical problem, one aspect needing research was FRC bond strength to enamel compared to conventional retainer material, which is generally stainless steel. Therefore, in this study, adhesive aspects of several FRC retainer materials were compared to that of a commonly used stainless steel orthodontic wire.

Mean bond strength results did not significantly differ between the FRC groups, although their compositions and textures were different. Except Ribbond, the other FRC materials used were silanized, pre-impregnated glass FRCs. Interestingly, between pre-impregnated glass FRCs and Ribbond, there were no significant differences. In fact, preimpregnation of fibers not only improves handling characteristics and enables a higher fiber volume, but also results in improved adhesion because of the semi-IPN (interpenetrating polymer network) structure of the polymer matrix.[13] Based on this information, one could expect more adhesive failures between the FRC and the flowable composite (failure types 3 or 5, see Table 2); however these failure types were not observed with the Ribbond fiber. The manufacturer of Ribbond suggests the use of any adhesive monomer for its pre-impregnation. In this study, Stick Resin was used for pre-impregnation. Apparently, this resin with a mixture of mono- and di-functional methacrylates was sufficient to achieve good adhesion of the flowable resin to the fibers.

The incidence of attached flowable composite on the enamel (failure types 1a and 1b) after debonding was more frequent in group 3 (everStick Ortho) than those of other groups, which indicates good adhesion compared to failure type 0. Although there were differences in terms of failure types, considering that the mean bond strength values between the FRC retainer groups did not differ signifi-

Table 3 Failure types and their distribution per experimental group for FRC or stainless steel wire retainers

Groups	Dislodged*	Score for type of failures							Cohesive enamel fracture
		0	1a	1b	2	3	4	5	
1	0	0	1	3	0	0	6	0	0
2	0	0	1	2	0	0	5	2	2
3	0	0	2	7	0	0	1	0	1
4	0	0	1	5	0	0	4	0	2
5	0	1	1	6	0	0	0	2	1
6	0	0	9	0	0	0	1	0	0
7	0	2	8	0	0	0	0	0	0
8	0	6	4	0	0	0	0	0	1

Score 0= no composite left on the enamel surface; score 1a= less than half of the composite left; score 1b= more than half of the composite left; score 2= cohesive failure within the base flowable resin; score 3= all composite left on the enamel surface, with a distinct impression of the FRC/wire; score 4= cohesive failure within the FRC separation/fracture of the wire; score 5= adhesive failure between the FRC/wire and the covering flowable resin.
*During thermocycling or testing. For group descriptions see Table 1.

cantly, the hypotheses could be partially rejected. The failure behavior of FRC materials is very complex because of their anisotropic character.[11,27,28,31] Laminated composites are known to have a relatively poor ability to absorb energy due to local impact damage.[33] For this reason, application of more fibers in a given composite volume may change the load bearing capacity of the whole structure. Clinically, however, this approach is not desirable and almost impossible; the splint should be kept at minimum thickness in order to avoid bulky constructions that may cause plaque accumulation and sometimes irritations for the tongue.

Static compression tests demonstrated that with the increasing fiber content, the flexural strength increases linearly.[5,18] This information is often derived from bar-shaped specimens prepared according to the ISO norms, where usually 2 mm of veneering composite was placed on the FRC material. Considering the geometry of the specimens prepared in this study, made to represent the clinical situation as closely as possible, and the insignificant differences between the four FRC materials, it can be stated that the adhesion of the flowable base composite is also one of the predominant factors that play a role in the bond strength results. On the other hand, considering the higher bond strength results obtained from the stainless steel wire groups vs those of some FRCs tested, it appears that

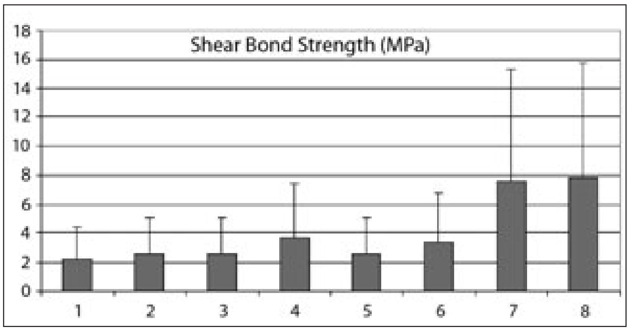

Fig 5 Mean shear bond strength results per experimental group.

the FRC actually weakens instead of strengthens the fiber/composite complex.

It was expected that the FRC materials would show higher bond strengths than the wire, because the adhesive properties between the fiber and the composite are chemical, contrary to those of the wire, which rely on mechanical retention. Reports on the causes of failure of bonded orthodontic wire retainers often indicate that the composite covering the wire is insufficient, resulting in detachment of the wire.[4] It was advised that by increasing the surface area (diameter) of the wire[3] or using less abrasive composite materials, debondings could be avoided.[4] However, Bearn et al[4] found no significant difference in the retention of differently shaped 3- and 6-stranded wires in a composite material. In another study, insufficient composite thickness was reported to play a major role in clinical failures.[10] Due to this contradiction, in this study, the retainers were completely covered with the flowable resin.

Comparative studies regarding the shear strength of FRCs incorporated into particulate resin composites on enamel generally showed no difference when compared to the control groups where no FRC was used.[16,17] A significant increase in shear strength was reported for some fibers,[16] but other studies showed no significant increase in shear bond strength.[16,28,29] Meiers et al[17] reported that a nonimpregnated fiber, Connect (Kerr; Orange, CA, USA), showed higher shear bond strengths than Ribbond (Seattle, WA, USA) and preimpregnated unidirectional woven Splint-it (Jeneric/Pentron; Wallingford, CT, USA). In that study, the specimens were thermocycled 1000 times. In an other study, Meiers et al[16] compared the same fiber materials and also found a significant increase in the shear bond strengths to enamel with the use of Connect, while the other fibers showed no significant difference compared to each other and the control flowable composite (Tetric Flow) without a fiber. In contrast, another study[28] found no significant differences between any groups when bond strengths of EverStick and StickTech's preimpregnated FRCs that were applied either directly on a bed of flowable composite (Tetric Flow) or in combination with particulate filler composite (Filtek Z250) on human enamel were compared. The addition of flowable composite did not improve bond strength values. It was also found that the addition of bidirectional or random continuous fibers (StickNet, everStickNet, and an experimental random FRC) did not yield any significant improvement in bond strength to enamel and dentin compared to the control of particulate filler composite (Filtek Z250).[29] In these studies, composites covering the fibers were 4 to 5 mm thick. Therefore, a different effect of reinforcement and crack propagation could be expected than in this study.

It should also be emphasized that in shear bond strength tests, the adherend is bonded to enamel surfaces that are not completely flat. Although an attempt was made to control this by using mandibular central incisors which have relatively more flat surfaces, the true shear stresses cannot be measured. Similarly, lingual retainers are placed on the lingual surfaces on the anterior teeth that present even more pronounced concavity.

In the shear-peel tests, the cutting blade was placed between the tooth surface and the flowable composite in such a manner that the cutting edge was as close to the enamel surface as possible. One could assume that what is being inadvertently measured is the adhesion of the composite rather than the effect of the wire or fiber. In this study, however, there were no significant differences between wire groups either when they were applied in the bed of flowable composite (groups 5 and 8) or directly on the bonding agent (groups 6 and 7). Furthermore, there were significant differences between some FRC groups (groups 1 and 2) and all the wire groups (groups 5 to 8). This clearly indicates that the debonding forces are diverted differently, regardless of whether there was flowable composite on the bonded surface or not. The height of the specimens was kept at 1.5 mm in order to achieve grasp of the blade in the universal testing machine. This was determined during the preliminary experiments. In clinical practice, this thickness may still be considered high. The dilemma remains of how to control the thickness of the flowable composite in bonded retainers clinically. It should also be emphasized that in shear bond strength tests, the adherend is bonded to enamel surfaces that are not completely flat. Although an attempt was made to control this by using lower central incisors which have relatively more flat surfaces, the true shear stresses cannot be measured. Similarly lingual retainers are placed on the lingual sufaces of the anterior teeth that present even promounced concavity.

The mean bond strength values of the FRC retainers in this study (6.1 to 8.4 MPa) were lower than those reported in other studies (14 to 23 MPa).[16,28,29] Several factors might have contributed to this result, such as application methods and materials,[26,29] the direction of the load on the fiber,[12,13,29] and storage conditions.[16,28,29] Reynolds and von Fraunhofer[24] reported that a minimum bond strength of 6 to 8 MPa could give a satisfying clinical performance and successful clinical bonding of brackets in orthodontics. The results obtained from the wire retainers (10 to 14 MPa) exceed these recommended values. However, in this study, specimens were thermocycled for 6000 cycles. It can be anticipated that the temperature elevations and water uptake of the adhesive resin might result in lower bond strength. Although the results obtained in all groups were within or exceeded this range, the recommended bond strength values should be evaluated with caution, because thermal or other types of aging procedures were not taken into consideration.[20-22,24] It should also be noted that the retainers are expected to remain intact as long as possible after orthodontic treatment, whereas a semi-permanent kind of adhesion is expected from the brackets. In this context, perhaps recommended adhesion values to etched enamel should serve as the golden standard, which is known to be on the order of 15 to 30 MPa.[14,33] In that respect, the bond strengths obtained in this study are not sufficient to function as well as restorative composites. The occurrence of enamel fractures indicates, however, that the adhesion exceeded the cohesive strength of the enamel itself in some cases in the FRC groups (5 enamel fractures out of 40 specimens). Enamel fractures may present a clinical problem during bracket debonding. Yet for lingual retainers, from which retention is desired to maintain the achieved orthodontic result for a long time, this aspect would not be considered a problem. Nonetheless, one could speculate that the failure is not only a result of adhesion or bond strength. After orthodontic treatment, when the teeth tend to revert to their original position, the interfacial forces might exceed the adhesive strength of the flowable composite to the tooth surface. In this case, variations between the flowable composites may affect the results. However, in this study, wire retainers bonded with either StickFlow or Tetric Flow composites presented no significant differences (groups 5 to 8). Although the results were higher (but not significantly), the group in which Heliobond was used as a bonding agent showed more adhesive failures (failure type 0) when compared to StickResin. This may be due to 2,2-bis[4-(2-hydroxy-3-methacryloxyropoxyl)]-phenonylpropane in the composition of the latter that might have better surface wettability properties.

In one clinical study by Rose et al,[25] 20 patients were randomly assigned to receive Ribbond fiber or multistranded wire retainers from canine to canine following the completion of orthodontic treatment. The retainers remained in place for an average of 11.5 and 23.6 months, respectively, with a statistically significant difference. This limited clinical evidence indicates that the multistranded wire is superior to the plasma-treated woven polyethylene ribbon, which is a nonpreimpregnated fiber. Nevertheless, both retainers presented unacceptable survival rates. Therefore, it can be concluded that orthodontists are still confronted with debonding of bonded retainers.

Fixed lingual retainers connect at least two teeth and are therefore certainly longer than 3 mm. One limitation of this study could be short length of the retainer compared to the clinical situation. Adhesion tests require some standardization before complex situations can be tested. Hence, this study solely dealt with the adhesive properties of various fibers placed at different locations and in different manners. Other factors, such as length and curvature of the teeth, had to be excluded in order to isolate the effect of the retainer type and location on the bond results. Because no significant difference has been found between bonding results to buccal and lingual surfaces,[8,35] the attempt was made to eliminate the convexity factor by using only the labial surfaces of the teeth for adhesion purposes.

Under the influence of compressive cyclic stresses, the damage associated with delamination may reduce the overall stiffness as well as the residual strength, leading to structural failure. The behavior of FRC and metal wires under fatigue conditions is being investigated in our laboratories.

CONCLUSIONS

1. Bond strength results did not significantly differ either between the FRC groups or the stainless steel wire groups. Only group 8, in which Heliobond and Tetric Flow were used and the wire was placed in the bed of the flowable resin, showed significantly higher mean bond strengths than those of DentaPreg Splint and Angelus Fibrex Ribbon.
2. Preimpregnated and custom impregnated FRC materials performed the same in terms of bond strength.
3. Changing the application mode of wire retainers did not result in significant changes in bond strength, but the failure modes showed variations between the experimental groups.

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Clinical relevance: Regardless of their application mode, stainless steel orthodontic bonded retainers delivered higher bond strengths than those of fiber retainers but the failure types varied between the tested materials.